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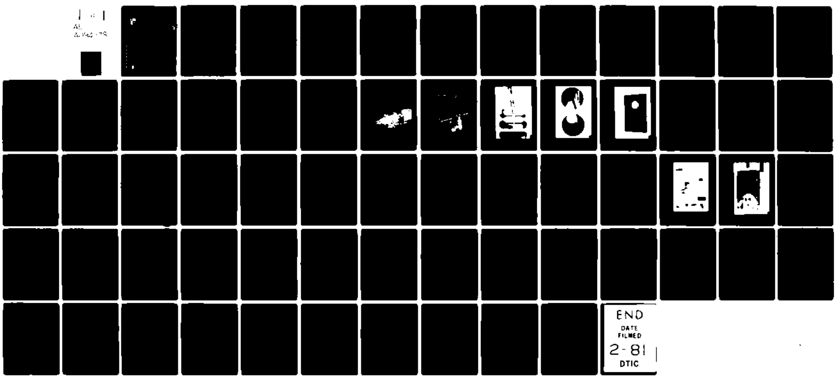

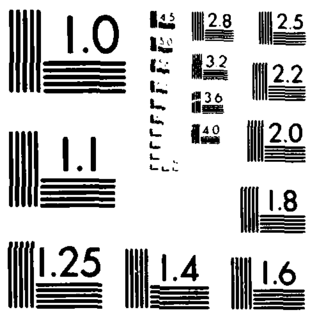

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(10) D. W. Stallings [redacted] M. O. King

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This report has been reviewed and approved.

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FOR THE COMMANDER

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The Space Shuttle Solid Rocket Booster Instrumentation Islands were tested at Mach numbers 1.75, 2.25, 3, and 10 for Reynolds numbers ranging from 0.6 x 10^6 to 4.74 x 10^6 per foot to evaluate potential error sources which might influence the flight test data. The test specimens were instrumented with flight transducers and with VKF transducers as reference standard. They were mounted on a wedge and tested at wedge angles ranging from 3 to 25 deg. In addition, for the Mach number 10 tests, the VKF infrared system was used to monitor the surface temperature of the test specimens.

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CONTENTS

APPENDIXES

NOMENCLATURE

ALPHI	Indicated sting pitch angle, deg
AO	Intercept of linear curve fit, see Eq. (7)
A1	Slope of linear curve fit, see Eq. (7)
B	Wedge width, in.
BLTi	Bond layer thermocouple identification number
C	Model material specific heat, Btu/lbm-°R
C1	Gardon/Schmidt Boelter gage calibration factor measured at 530°R, Btu/ft^2-sec/mv
C2	Temperature corrected Gardon gage calibration factor, Btu/ft^2-sec/mv
CONFIG	Model configuration designation
DBOT	Instrument island bottom diameter, in. (see Fig. 4)
DTOP	Instrument island top diameter, in. (see Fig. 4)
E	Gardon gage output, mv
F-STOP	Infrared camera f-stop; ratio of aperture to focal length
GAGE	Gage identification number
H	Instrument island height, in. (see Fig. 4)
HCi	Hi-cal gage identification number
HE	Instrument island edge step, in. (see Fig. 4)
H(RTT)	Heat-transfer coefficient based on assumed recovery temperature R·TT, $\frac{QDOT}{R \cdot TT-TW}$, Btu/ft^2-sec-°R
H(TAW)	Heat-transfer coefficient based on experimentally determined TAW, QDOT/(TAW-TW), Btu/ft^2-sec-°R
H(TT)	Heat-transfer coefficient based on TT, QDOT/(TT-TW), Btu/ft^2-sec-°R
KG	Gardon gage temperature calibration factor, °R/mv

L	Wedge length, 41.5 in.
M	Free-stream Mach number
MGGi	Model Gardon gage identification number
MTi	Med-therm gage identification number
MU	Dynamic viscosity based on free-stream temperature, lbf-sec/ft^2
P	Free-stream static pressure, psia
PGi	Calibration plate Gardon gage identification number
PT	Tunnel stilling chamber pressure, psia
PTC	Temperature of lower surface of island support plates for Tunnel C models, °R
Q	Free-stream dynamic pressure, psia
QCW	Calculated cold wall heat-transfer rate based on TW = 0 °F, Tunnel A, Btu/ft^2-sec
QDOT	Heat transfer rate, Btu/ft^2-sec
QDOT-0	Tunnel C nomenclature for QCW parameter, Btu/ft^2-sec
R	Assumed adiabatic wall temperature ratio, TAW/TT
RE	Free-stream unit Reynolds number, ft^{-1}
RHO	Free-stream density, lbm/ft^3
RUN	Data set identification number
SENS	Infrared monitor sensitivity setting
T	Free-stream static temperature, °R or °F
TAW	Adiabatic wall temperature, °R or °F
TGDEL	Temperature differential between the center and edge of the Gardon gage disc, °R or °F
TGE	Gardon gage edge temperature, °R or °F
TIME	Elapsed time from lift-off, sec

TP	Temperature of lower surface of island support plate for Tunnel A models, °R
TR	Assumed recovery temperature, °R or °F
T_{ref}	Temperature of reference surface for infrared data, °R
TT	Tunnel stilling chamber temperature, °R or °F
TW	Model surface temperature, °R or °F
V	Free-stream velocity, ft/sec
WA	Wedge angle, deg
WGi	Wedge-mounted Gardon gage identification number
X, Y	Orthogonal body axis system directions (see Fig. 4)
θ	Island bevel angle, deg (see Fig. 4)
ε	Emissivity of model surface
ε_{ref}	Emissivity of reference surface

1.0 INTRODUCTION

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 921E02, Control Number 9E02-00-9, at the request of Marshall Space Flight Center, NASA/MSFC - ED33 for Remtech, Inc. The NASA/MSFC project monitor was Mr. E. B. Brewer and the Remtech projett monitor was Dr. Carl Engel. The results were obtained by ARO, Inc., AEDC Group (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee. The test was conducted in the von Kármán Gas Dynamics Facility (VKF) Supersonic Wind Tunnel (A) and Hypersonic Wind Tunnel (C) on January 14-15 and May 2 and 5, 1980, under ARO Project No. V41A/C-B1.

When the Space Shuttle is launched, the Solid Rocket Boosters (SRB) will have several "instrument islands" attached, consisting of an instrument module enclosed by protective insulation material. Calorimeters in the instrument modules will measure heating rates during flight. In order to use the information thus obtained, it is necessary that possible measurement-induced errors in the data be evaluated. The purpose of this wind tunnel test program was to quantify the measurement-induced errors in the calorimeter readings by testing a variety of calorimeter installations. The different installations were intended to permit uncoupling of the various error source effects, such as geometry, ablation, and temperature mismatch between the calorimeter and the surrounding insulation material.

The tests were conducted in the 40- by 40-in. Supersonic Wind Tunnel (A) and the 50-in. diameter Hypersonic Wind Tunnel (C) at wedge angles up to 25 deg. The tests in Tunnel A were at Mach numbers 1.75, 2.25, and 3.0, with Reynolds numbers ranging from 0.6×10^6 to 4.74×10^6 per foot. The Tunnel C tests were at Mach number 10 and a Reynolds number of 2.20×10^6 per foot.

All test data, including detailed logs and other information required to use the data, have been transmitted to Remtech. Inquiries to obtain copies of the test data should be directed to NASA/MSFC - ED33, Huntsville, Al 35812. A microfilm record has been retained in the VKF at AEDC.

2.0 APPARATUS

2.1 TEST FACILITIES

Tunnels A and C are continuous, closed-circuit, variable density wind tunnels. Tunnel A (Fig. 1) has an automatically driven flexible-plate-type nozzle and a 40- by 40-in. test section. The tunnel can be operated at Mach numbers from 1.5 to 6 at maximum stagnation pressures from 29 to 200 psia, respectively, and stagnation temperatures up to 750°R at Mach number 6. Minimum operating pressures range from about one-tenth to one-twentieth of the maximum at each Mach number.

Tunnel C (Fig. 2) is a hypersonic wind tunnel with a Mach number 10 axisymmetric contoured nozzle and a 50-in.-diam test section. The tunnel can be operated continuously over a range of pressure levels from 200 to 2000 psia with air supplied by the VKF main compressor plant. Stagnation temperatures sufficient to avoid air liquefaction in the test section (up to 2260°R) are obtained through the use of a natural gas fired combustion heater in series with an electric resistance heater. The entire tunnel (throat, nozzle, test section, and diffuser) is cooled by integral, external water jackets. Both tunnels are equipped with a model injection system, which allows removal of the model from the test section while the tunnel remains in operation.

A description of the tunnels may be found in Ref. 1.

2.2 TEST ARTICLES

Six categories of models were used to investigate the different error sources mentioned in Section 1.0. The general construction and form of these models can be seen in Figs. 3 and 4. A 15 x 24 inch flat plate was fitted with the instrument island and transducers to be tested. This assembly was then mounted on a large wedge specimen holder (Fig. 3).

The six model categories used are summarized in Table 1, along with the model type identification for each category. Note that model types A, B, C, D, and E were used only in Tunnel C while types F, G, and H were used only in Tunnel A. Details of each type are presented in Figure 5 and Table 2, and the six categories are described below:

(1) Types A and F were flat steel calibration plates used to obtain general heating levels and distributions at the various test conditions (Fig. 5a and 5k).

(2) Type B was also a flat plate, but with transducers mounted in a nonmetal, nonablating material (chopped silica cloth phenolic). The portion of the plate ahead of the instrumented section was either steel or silica phenolic (Fig. 5b).

(3) Type C was a steel plate with a silica phenolic island (Fig. 5c and 5d).

(4) Type D was similar to A and B, but with ablating surfaces, one cork and one MSA (Fig. 5e).

(5) Type E was a duplicate of the actual flight hardware installation (Fig. 5f through 5j).

(6) Types G and H, for use in Tunnel A only, were steel plates with replaceable steel islands (Fig. 5k).

It can be seen that the design of the models was such as to divide the overall test objectives between the two tunnel entries. The Tunnel A models utilized steel islands in a steel plate with only VKF transducers. The primary variable for this test entry was the island geometry relative to the boundary layer thickness. The boundary layer

conditions depend on the local Mach number and Reynolds number. These are varied by changing the tunnel Mach number, free-stream Reynolds number, or adjusting the wedge angle. The Tunnel C models were designed to evaluate ablation, temperature mismatch effects, and flight instrumentation.

Representative sketches of the models installed in the tunnels are depicted in Fig. 6. For the Tunnel C installation the approximate IR field-of-view is indicated.

2.3 TEST INSTRUMENTATION

The measuring devices, recording devices and calibration methods used for all measured parameters are listed in Table 3 along with the estimated measurement uncertainties. A variety of heat flux gages were supplied by VKF to obtain heat transfer rate measurements: 10 mil, 0.25 in. diameter conventional high temperature Gardon gages; 10 mil, 0.25 in. diameter thermopile Gardon gages; and 0.25 in. diameter Schmidt-Boelter gages. In addition, for the Tunnel C tests three conventional Gardon-type gages (Hy-Cal) and two Schmidt-Boelter gages (Medtherm) were provided by Remtech, Inc. Although Remtech received calibration constants with their gages, prior discrepancies between VKF and Hy-Cal/Medtherm calibration factors warranted calibration of all gages at the VKF. A discussion of the discrepancies is presented in Appendix III.

The VKF thermopile gage utilizes vapor-deposited layers of antimony and bismuth to form a thermopile on the back surface of the sensing foil. A gage size of 0.25 in. with a sensing foil thickness of 0.010 was used. The gages were instrumented with either iron-constantan or Chromel-® 1-Alumel® thermocouples which provided the gage edge temperature measurement. The VKF Schmidt-Boelter gage consists of a thermopile wound around a thin slab of medium conductivity material, and temperature differences across the slab are measured. This construction provides a high sensitivity gage with output directly proportional to the incident heat flux on the gage surface. Gage edge temperatures together with the thermopile output were used to determine the gage surface temperatures and corresponding gage heat transfer rate. These data were then used to compute the local heat transfer coefficient.

Heat-transfer coefficients cannot be obtained directly from the Hy-Cal and Medtherm transducer data because these gages were fabricated without thermocouples for measuring the gage edge temperature. Before delivering the transducers to VKF, Remtech technicians used conductive epoxy to bond two thermocouples to the outside of each gage, one on the base and one near the top as close to the sensing foil as possible. Data from these thermocouples will be used by Remtech in developing math models of the transducers, from which computer code predictions of gage surface temperature can be made. This, with the measured gage heat-transfer rate, QDOT, will then allow calculations of the heat-transfer coefficient.

The general arrangements of the model instrumentation are included in Fig. 5 and dimensional locations of the gages are listed in Table 4. Note that model types F, G, and H (Tunnel A models) used only VKF transducers. The Hy-Cal and Medtherm calorimeters were used only in the Tunnel C models.

For the Tunnel C tests, an infrared system was used to monitor model surface temperature. This system utilizes an AGA Thermovision 680 camera which scans at the rate of 16 frames per second. This camera has a detector which is sensitive to infrared radiation in the 2 to 6 micron wavelength band. The camera output was recorded on analog tape and simultaneously displayed on a color video monitor. The increase in model surface temperature with time was thus observed. A permanent record of the temperature patterns was obtained by photographing the monitor screen one or more times during the heating process. A complete description of the system is given in Ref. 3.

For those island specimens which included an ablating panel, photographic coverage was provided by a 16mm motion picture camera which viewed the model through a port on top of the tunnel.

Instrumentation outputs were recorded using the VKF digital data scanner in conjunction with the VKF analog subsystem. Data acquisition from all instruments other than the infrared camera was under the control of a PDP 11/40 computer, utilizing the random access data system (RADS).

A given injection cycle is termed a run, and all the data obtained are identified in the tabulations by a run number.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS

A summary of the nominal test conditions at each Mach number is given below.

M	PT, psia	TT, °R	RE x 10^{-6}/ft
1.75	17.0	640	3.8
↓	7.5	640	1.7
↓	2.5	640	0.6
2.25	26.0	640	4.7
3.01	37.0	680	4.1
10.10	1765.0	1900	2.2

At some test conditions in Tunnel A, particularly at sub-atmospheric stagnation pressures, the air humidity level affects the test section Mach number. The Tunnel A sidewall Mach number probe is used periodically when testing at these conditions to monitor deviations from the standard calibrated Mach numbers. When a deviation is measured, the free-stream conditions are corrected and the actual Mach number is printed on the data tabulations.

A test summary showing all configurations tested and the variables for each is presented in Table 5.

3.2 TEST PROCEDURES

In the VKF continuous flow wind tunnels (A and C), the model is mounted on a sting support mechanism in an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank and the safety door seals the tunnel from the tank area. After the model is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, the model is injected into the airstream, and the fairing doors are closed. After the data are obtained, the model is retracted into the tank and the sequence is reversed with the tank being vented to atmosphere to allow access to the model in preparation for the next run. The sequence is repeated for each configuration change. The initial step prior to recording the test data is to cool the model uniformly to approximately 60°F with cooled high pressure air provided by a cooling manifold. When the cooling cycle is complete, the model attitude is established prior to tunnel injection. The model is then injected into the flow. At model lift-off the tunnel flow parameters are recorded and the data acquisition sequence for the Gardon gages is initiated prior to reaching the tunnel flow.

Tunnel A data were recorded at 4 second intervals for each gage over a period of approximately 4 minutes until the output of each gage approached zero. Tunnel C data were recorded every 4 seconds, for most runs, over a period of approximately 1 minute, depending on the model configuration being tested. Configurations E4 and E5 were inserted for approximately 7 minutes. Upon termination of the data recording sequence, the model was retracted from the tunnel and the cooling cycle was repeated.

As discussed in Section 2.3, the output of the IR camera is displayed in real time on a color television monitor. A 70-mm camera was used to photograph the monitor screen. On the television monitor the total temperature range which the system is set up to measure is divided, in a nonlinear fashion, into ten separate colors, starting with blue for the lowest temperature and progressing through white for the highest. Each color then represents a temperature band within the total range, and the interface between two colors corresponds to one particular temperature.

The color photographs of the infrared monitor can be used to obtain surface temperature if a calibration of color versus temperature is known. Such a calibration is a function of the sensitivity setting of the monitor, the camera f-stop, and the material emissivity. The temperatures at the nine color interfaces have been calculated for the f-stop/sensitivity combinations used in this test. Since exact values of the model emissivities were not available, 0.67, 0.89 and 0.92 were used. These numbers correspond to emissivities of cork, charred cork, and charred MSA respectively. These numbers were obtained from previous tests and should only be used as guidelines to evaluate the temperatures. Interface temperatures have been tabulated for each value of emissivity and are presented in Table 6. A sample photograph of the infrared display is shown in Fig. 7.

All of the Tunnel C ablation runs were recorded with a 16mm movie camera for future study. Pretest and posttest photographs of the sample were also taken. Typical pretest and posttest photographs are presented in Fig. 3c and Fig. 8, respectively.

3.3 DATA REDUCTION

For Tunnel A, free-stream parameters were computed assuming a perfect gas isentropic expansion from the tunnel stilling chamber, and utilizing the measured pressure and temperature at the stilling chamber and the calibrated Mach number at the test section. For Tunnel C, free-stream pressure and temperature have real gas corrections applied.

Data measurements obtained from the thermopile Gardon gages are gage output (E) and gage edge temperature (TGE). The gages are direct reading heat flux transducers and the gage output is converted to heating rate by means of a scale factor obtained from laboratory calibration (C1). The scale factor has been found to be a function of gage temperature and therefore must be corrected for gage temperature changes,

$$C2 = C1\ f(TGE) \tag{1}$$

Heat flux to the gage is then calculated for each data point by the following equation:

$$QDOT = (C2)(E) \tag{2}$$

The gage wall surface temperature used in computing the gage heat transfer coefficient is obtained from two measurements; the output of the gage edge thermocouple (TGE) and the temperature difference (TGDEL) from the gage center to its edge. The temperature difference (normally less than 15°F) is determined from the gage output and a laboratory calibrated scale factor (KG) as follows:

$$TGDEL = (KG)(E) \tag{3}$$

The gage wall temperature is then computed as

$$TW = TGE + 0.75\ TGDEL \tag{4}$$

where the factor 0.75 represents the average, or integrated value across the gage.

In Tunnel A, the "optional" Gardon gage data reduction procedure was used to compute local heat transfer coefficients and the corresponding recovery temperature (TAW). This technique is important in Tunnel A where the difference between the model wall and recovery temperature is relatively small (i.e., <200 °F). This small temperature difference causes the calculation of heat transfer coefficient to be very sensitive to deviations from the actual recovery temperature. The data reduction procedure is based on the definition of convective heat transfer coefficient and the assumption of negligible conduction and radiation. We have

$$H(TAW) = \frac{QDOT}{TAW-TW} \tag{5}$$

where H(TAW) and TAW are assumed constant. Rearranging Equation (5) gives

$$QDOT = [H(TAW)][TAW] - [H(TAW)][TW]. \tag{6}$$

where [H(TAW)][TAW] is a constant. Equation (6) can be written in the form of a straight line:

$$QDOT = A0 + A1(TW) \tag{7}$$

A comparison of Equations (6) and (7) gives

$$H(TAW) = -A1 \tag{8}$$

and setting QDOT = 0 in Equation (7) and solving for TW leads to the following relationship for TAW:

$$TW_{(QDOT\,=\,0)} = TAW = -\frac{A0}{A1} \tag{9}$$

The actual steps in the data reduction procedure are to obtain a linear curve fit of QDOT versus TW* for each gage (a typical plot is shown in Fig. 9) and evaluate A0 and A1 in Equation (7). The quality of the curve fit is verified by examining the plotted data on a graphics display terminal. When the curve fit has been verified, the heat-transfer coefficient can be calculated from Equation (8) and the adiabatic wall temperature can be determined from Equation (9). The value of TAW is checked to see if it is within the following range:

$$0.8 \leq \frac{TAW}{TT} \leq 1.01 \tag{10}$$

If Equation (10) is not satisfied, an asterisk is printed next to the value of TAW in the tabulated data.

The "standard" Gardon gage data reduction procedure was used to compute model local heat transfer coefficients in Tunnel C. The procedure averages five consecutive samples of gage output (E) commencing with the data loop recorded at least one second after the model arrives at tunnel centerline. The average output is then compared to each individual reading used in the average to check for "wild" points. If the individual readings differ from the calculated average by more than ±2 percent or ±15 counts, whichever is larger, an asterisk (*) is printed next to the tabulated value of QDOT. The gage edge temperature (TGE) was averaged in the same manner with ±5 deg allowable deviation from the average.

The heat transfer coefficient for each gage was computed using the following equation

$$H(TT) = \frac{QDOT}{(TT - TW)} \tag{11}$$

where QDOT and TW were obtained from gage measurements.

---

*Deviation from a linear curve can be indications of conduction and/or radiation.

Data measurements obtained from the VKF Schmidt-Boelter gages used in Tunnel C are gage output (E) and gage wall temperature (TW). These gages are also direct reading heat flux transducers, and the gage output is converted to heating rate by means of the scale factor obtained from laboratory calibration (C1). The temperature dependence of the Schmidt-Boelter gages has not yet been established, thus, the heat flux to the gage is calculated for each data point by the following equation:

$$\mathrm{QDOT} = (\mathrm{C1})(\mathrm{E}) \qquad (12)$$

Using these values of QDOT and TW, the heat transfer coefficient is calculated from Equation (11) which was then used to compute the cold wall heating rate QDOT-0, for TW = 459.67°R.

Equation 12 was also used to calculate QDOT from the output of the Hy-Cal and Medtherm gages. As discussed in Section 2.3 the evaluation of heat-transfer coefficient will depend on posttest analysis of the data from the thermocouples bonded to these gages. An interim calculation is included in the tabulated data, using Equation 11 with the wall temperature set equal to the temperature sensed by the thermocouple bonded to the gage case near the foil. This will give an approximate value of heat-transfer coefficient which should be useful during preliminary data analysis.

In addition to computing the heat transfer coefficient using TT as the assumed wall recovery temperature (TR) an additional coefficient was computed using an assumed TR of R•TT in order to more closely approximate TAW and H(TAW).

$$\mathrm{H(RTT)} = \frac{\mathrm{QDOT}}{(\mathrm{R \cdot TT - TW})} \qquad (13)$$

The use of two assumed values of TR provides an indication of the sensitivity of the heat-transfer coefficient to the value of TR assumed. As can be noted in the tabulated data, there are large percentage differences in the values of the heat-transfer coefficients calculated from the two assumed values of TR. Therefore, in the analysis of these data, the value selected for TR/TT is obviously very important.

3.4 UNCERTAINTY OF MEASUREMENTS

In general, instrumentation calibrations and data uncertainty estimates were made using methods recognized by the National Bureau of Standards (NBS). Measurement uncertainty is a combination of bias and precision errors defined as:

$$U = \pm(B + t_{95}S)$$

where B is the bias limit, S is the sample standard deviation and t_{95} is the 95th percentile point for the two-tailed Student's "t" distribution (95-percent confidence interval), which for sample sizes greater than 30 is taken to be equal to 2.

Estimates of the measured data uncertainties for this test are given in Table 3a. The data uncertainties for the measurements are determined from in-place calibrations through the data recording system and data reduction program.

Propagation of the bias and precision errors of measured data through the calculated data was made in accordance with Ref. 4 and the results are given in Table 3b. No estimate was made of the uncertainty of the measurements made with the Remtech supplied gages (see Appendix III).

4.0 DATA PACKAGE PRESENTATION

Sample data tabulations are presented in Appendix IV. In addition to the tunnel conditions, the measured QDOT and TGE and the calculated H(TT), H(RTT) and QDOT-0 are tabulated for each run. The camera parameters F-STOP and SENSITIVITY are also included in the tabulated data to aid in evaluating interface temperatures from infrared photographs.

In addition to the tabulated data, machine generated plots were made of QDOT and H(RTT) vs axial distance (X/L). Examples of these plots are shown in Fig. 10. Reasonable agreement can be seen between the gage data and VKF theory. An example of gage repeatability is presented in Figure 10c. Data are presented from three Tunnel C runs with the same tunnel conditions and wedge angle. The wedge gages, WG1-WG5, are seen to repeat very well from run to run. Models C1 and C2 are, as shown in Figure 5, identical except for the island heat gage. In Figure 10c the two gages are seen to be in good agreement. Model C3 is similar to the other two but with a slightly different island shape. The measured island heat-transfer coefficient is noticeably different. Evaluation of such effects was of course the basic purpose of the test program.

REFERENCES

1. Test Facilities Handbook (Eleventh Edition). "von Kármán Gas Dynamics Facility, Vol. 3." Arnold Engineering Development Center, June 1979.

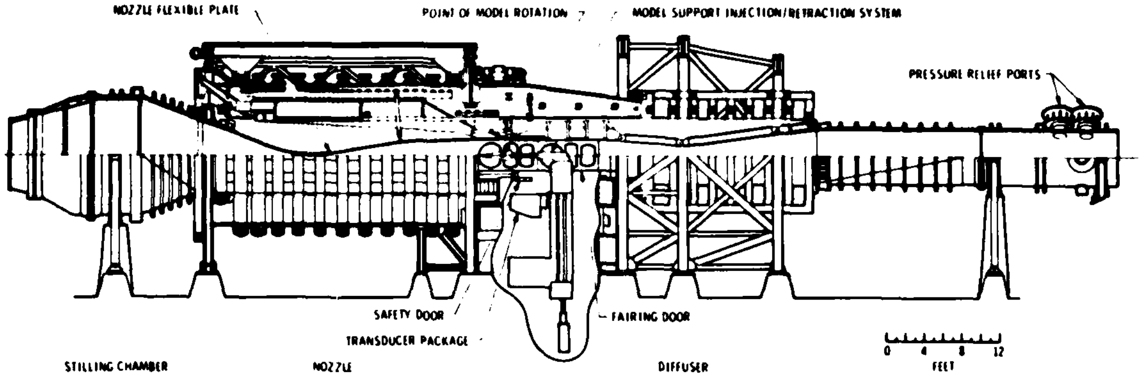
2. Trimmer, L. L., Matthews, R. K., and Buchanan, T. D. "Measurement of Aerodynamic Heat Rates at the AEDC von Kármán Facility." International Congress on Instrumentation in Aerospace Simulation Facilities, IEEE Publication CH0748-9AES, September 1973.

3. Boylan, D. E., Carver, D. B., Stallings, D. W., and Trimmer, L. L. "Measurement and Mapping of Aerodynamic Heating Using a Remote Infrared Scanning Camera in Continuous Flow Wind Tunnels." AIAA Paper No. 78-799, April 1978.

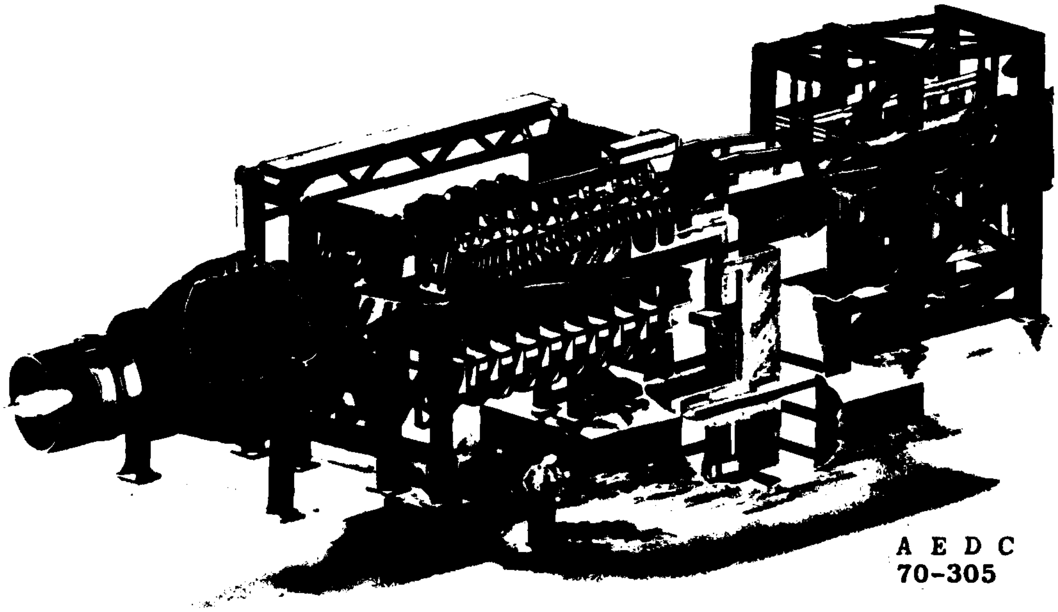
4. Abernethy, R. B. et al. and Thompson, J. W. "Handbook of Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD755356), February 1973.

APPENDIX I

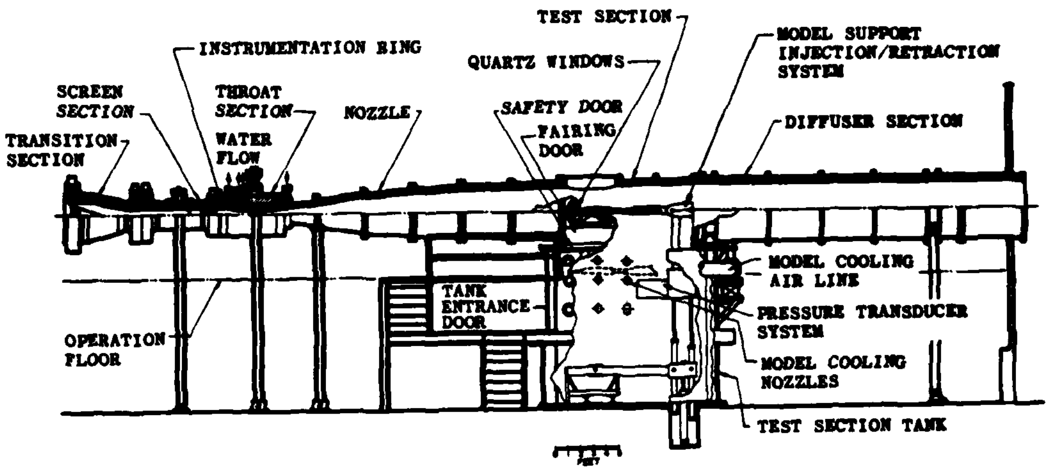
ILLUSTRATIONS



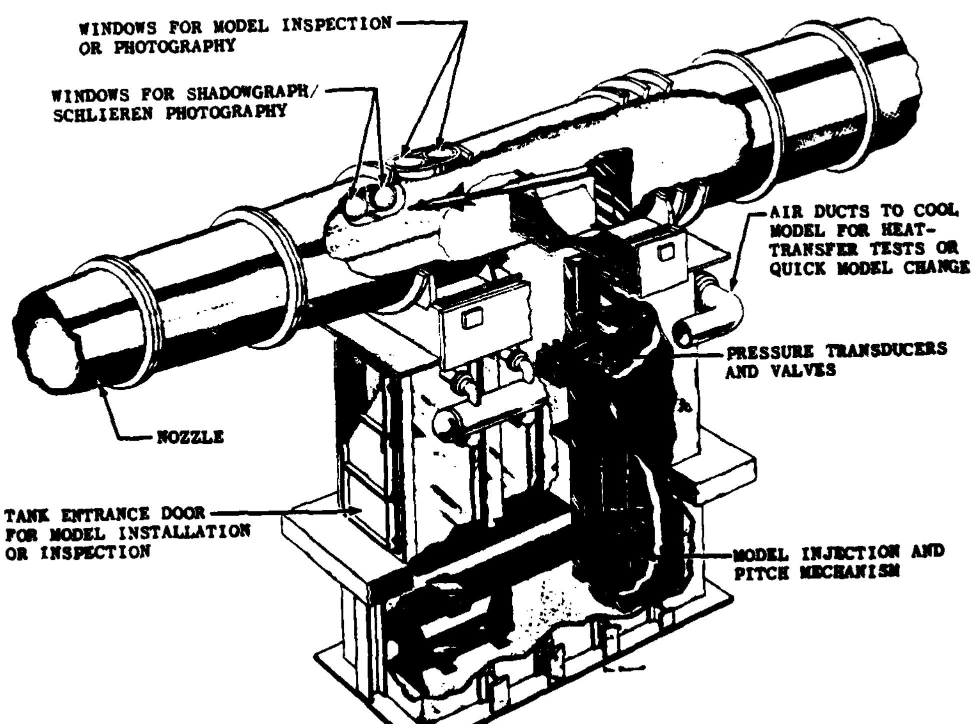
a. Tunnel assembly



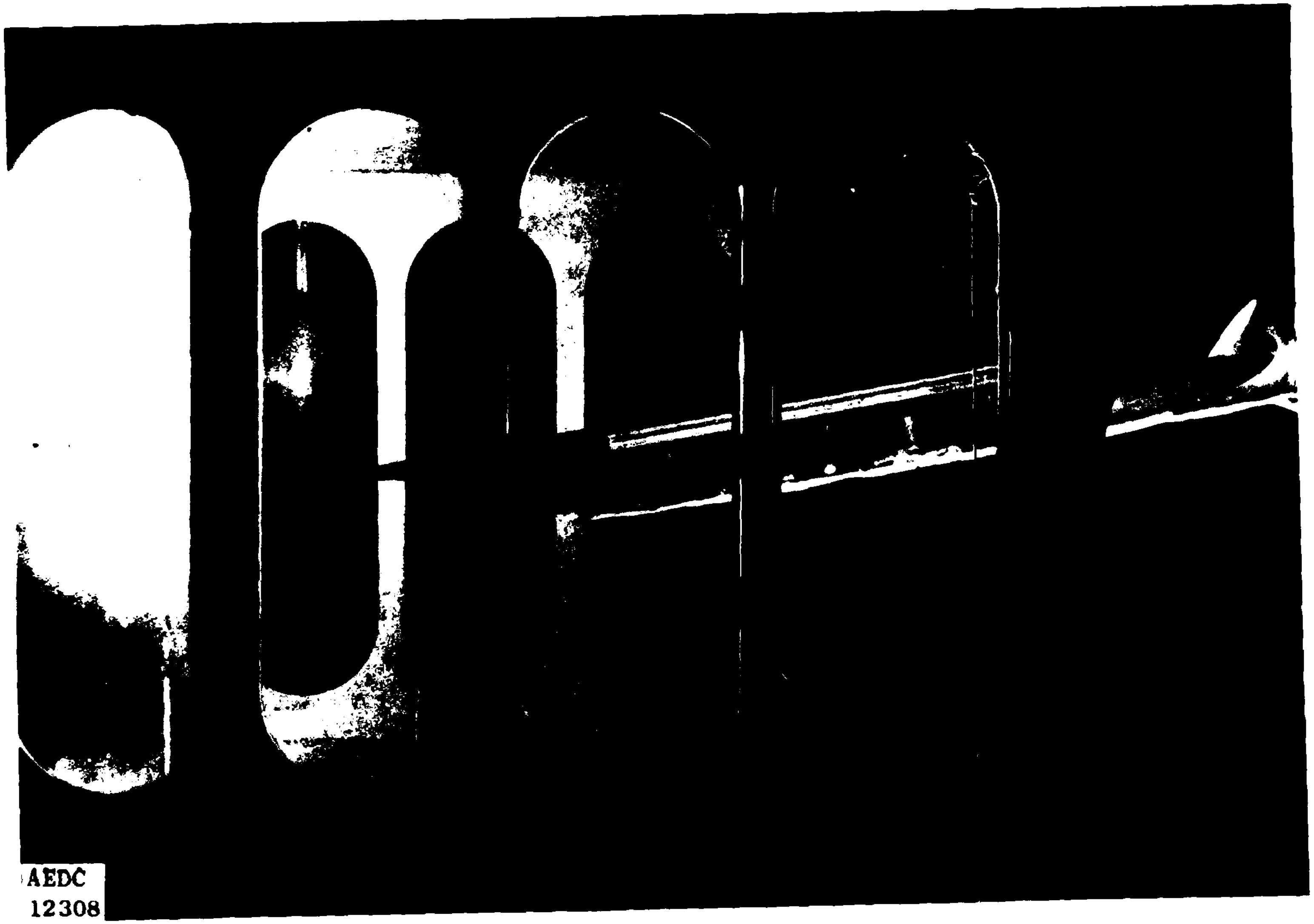
b. Tunnel test section
Fig. 1 Tunnel A



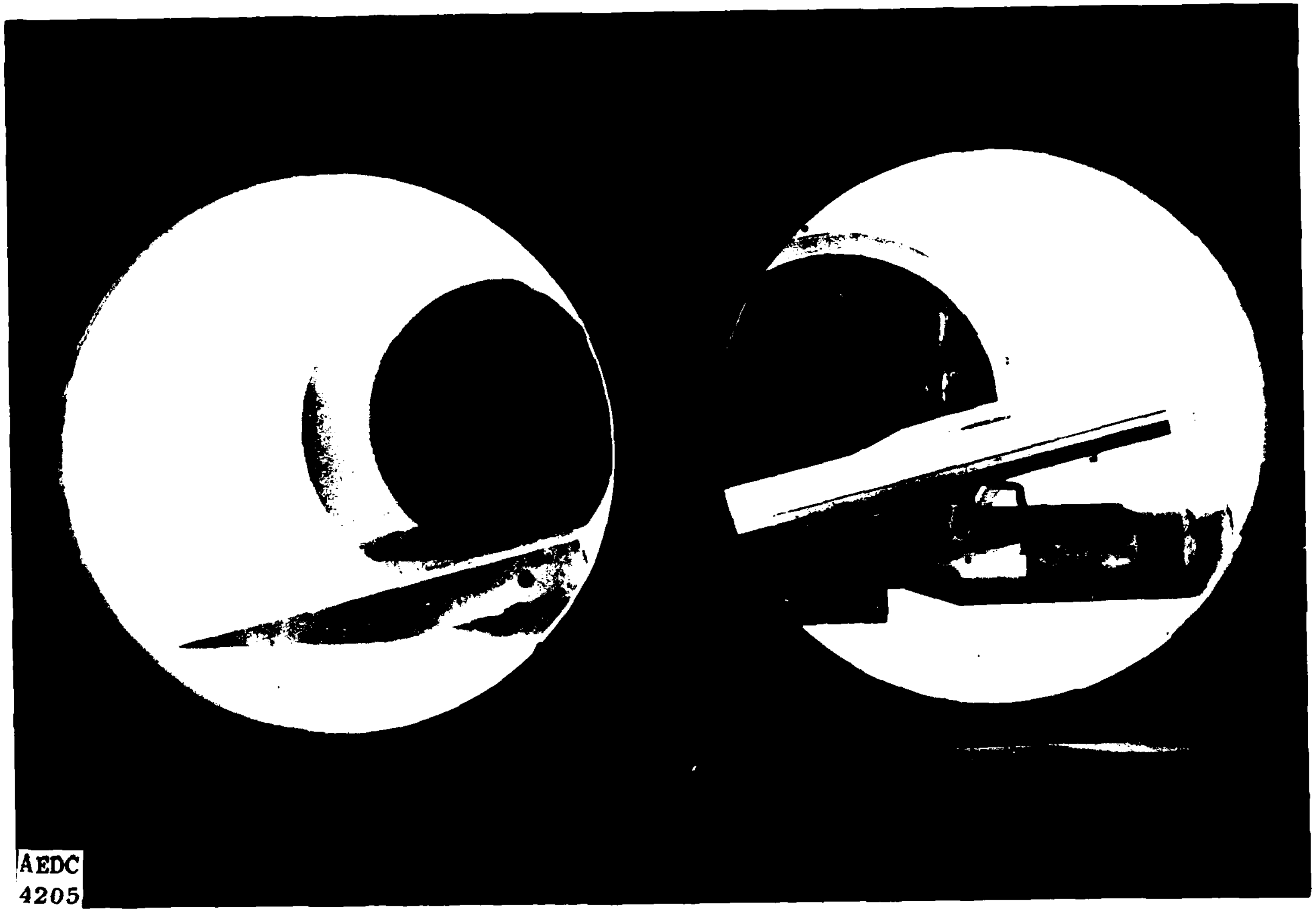
a. Tunnel assembly



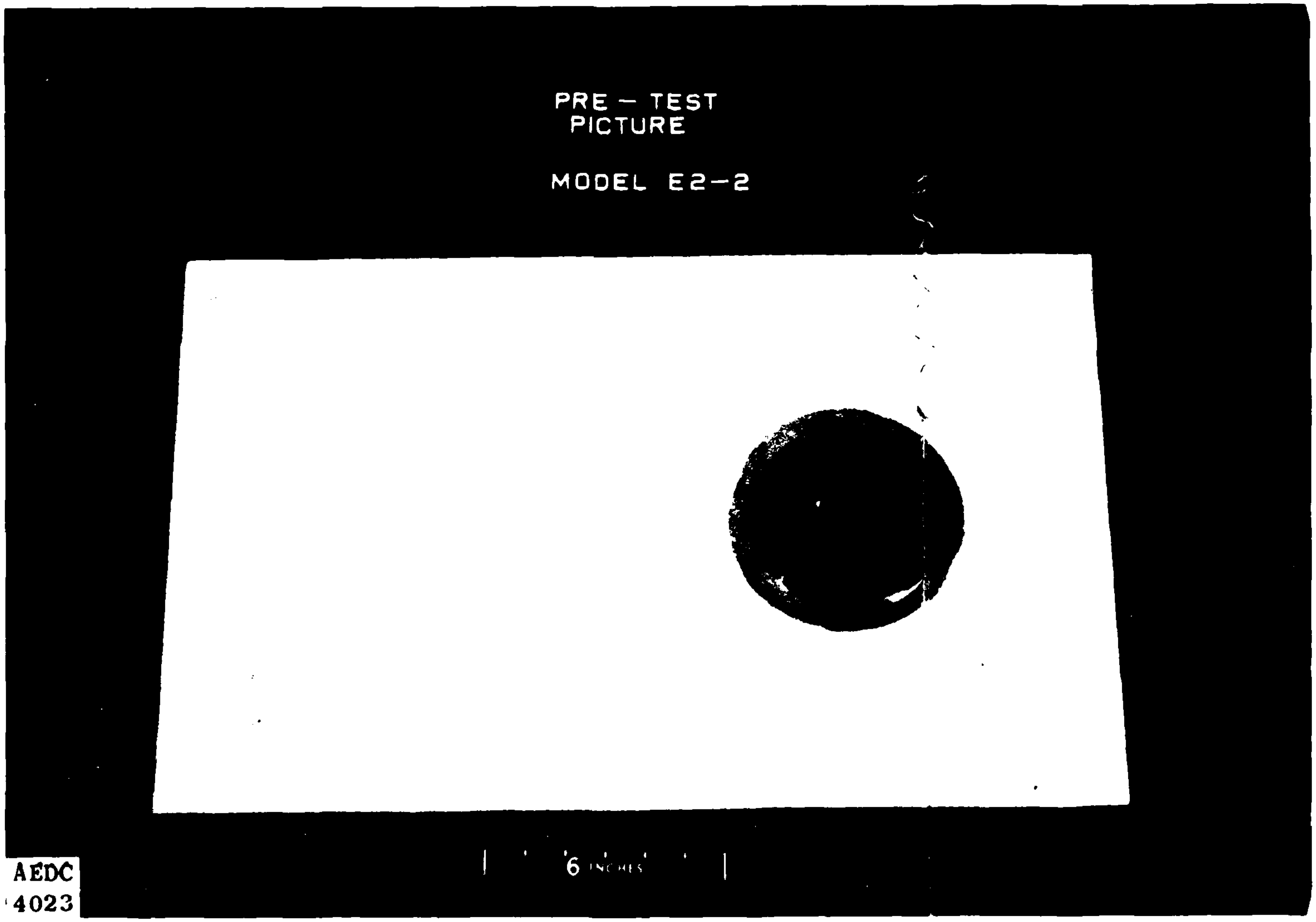
b. Tunnel test section
Fig. 2 Tunnel C



a. Tunnel A Installation
Fig. 3. Model Photographs



b. Tunnel C Installation
Fig. 3. Continued



c. Typical Pretest Photograph
Fig. 3. Concluded

All dimensions in inches

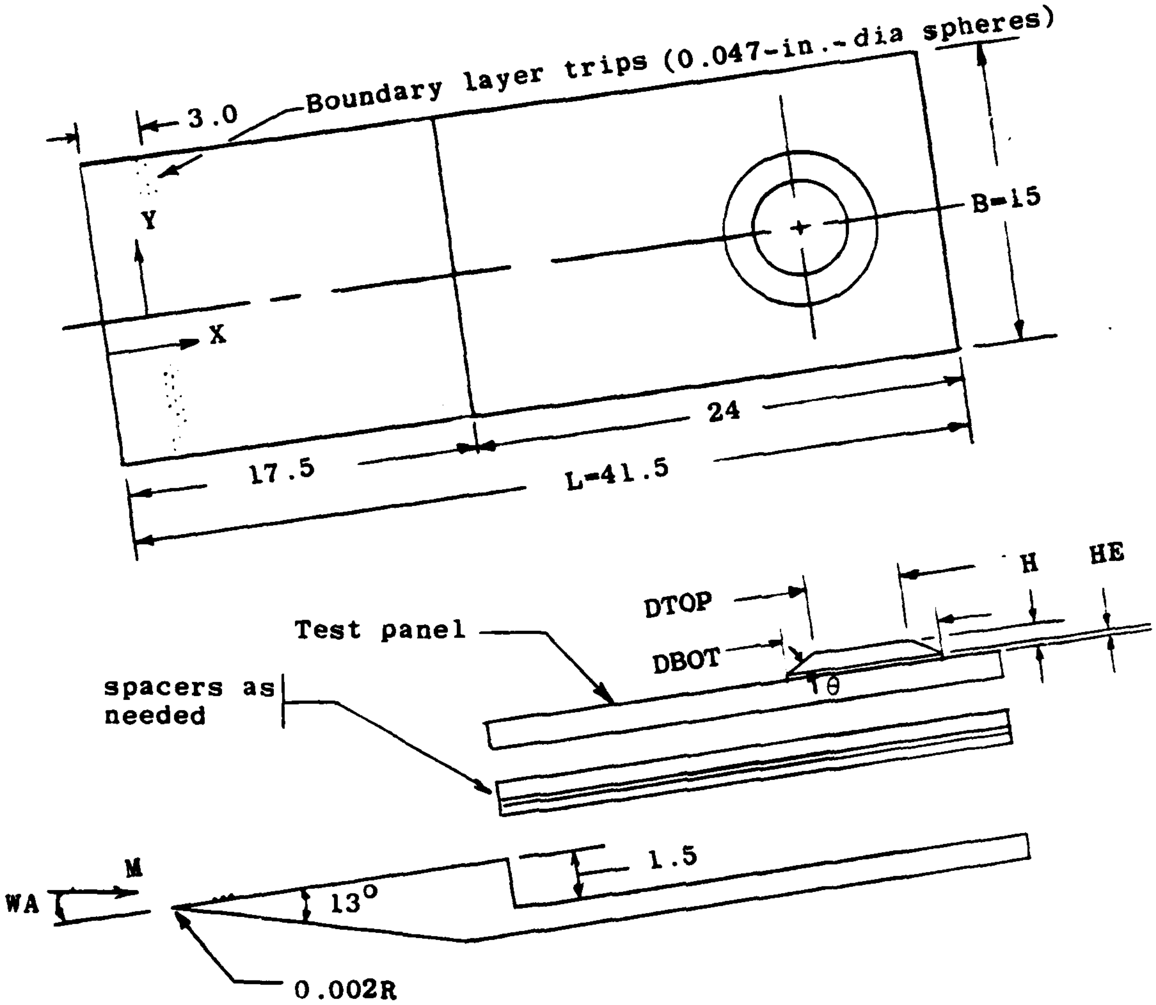
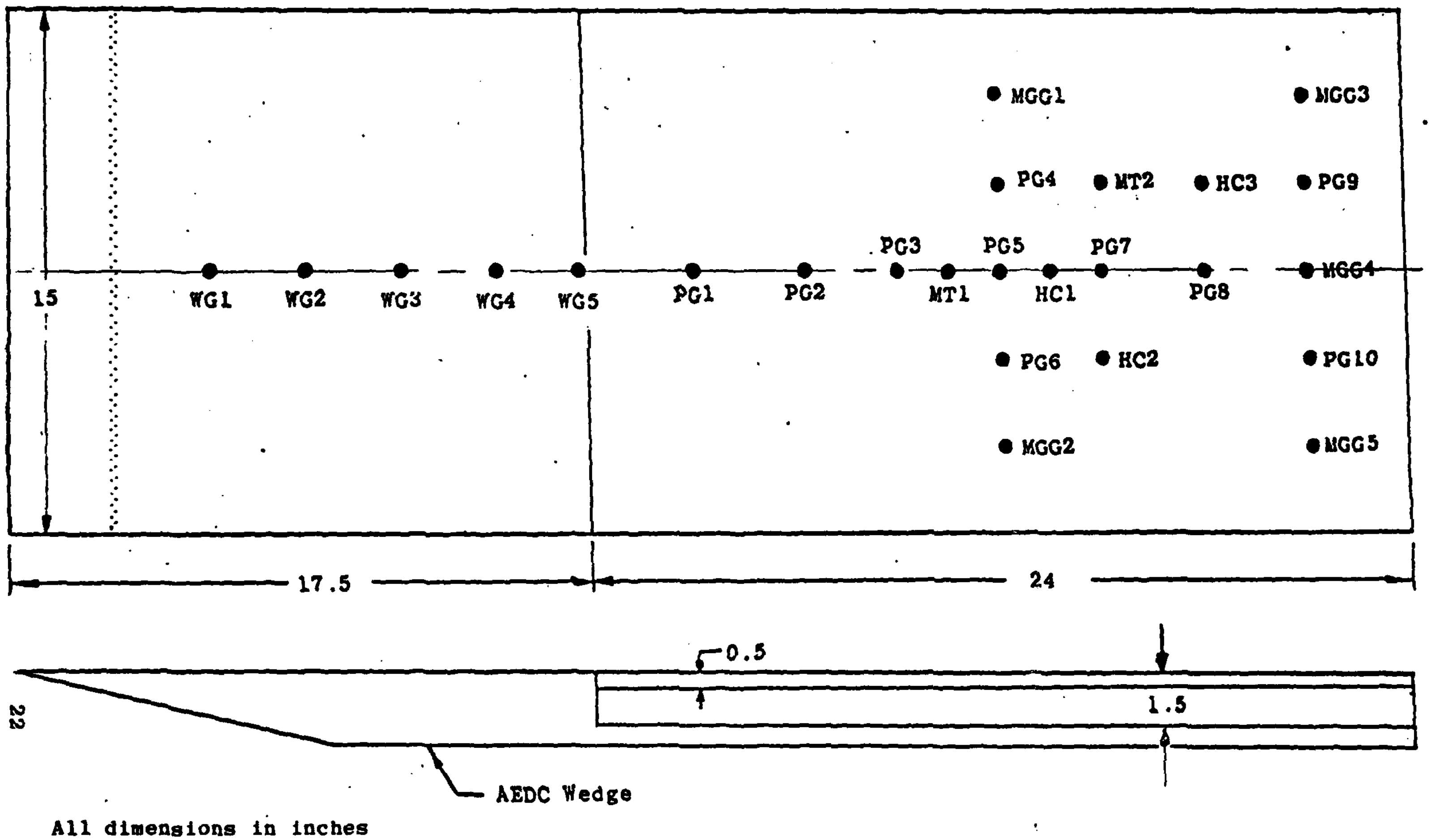
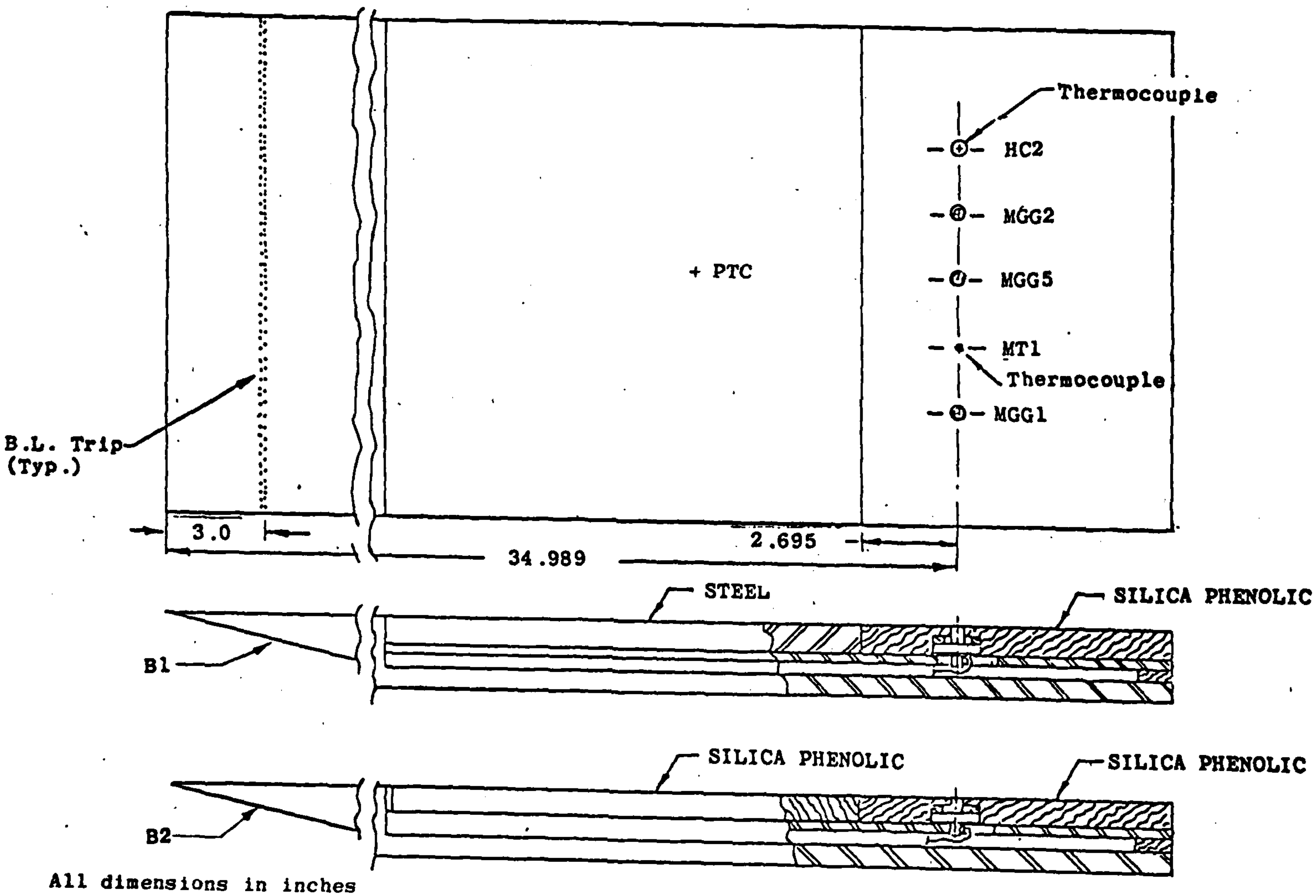


Figure 4. General Model Schematic

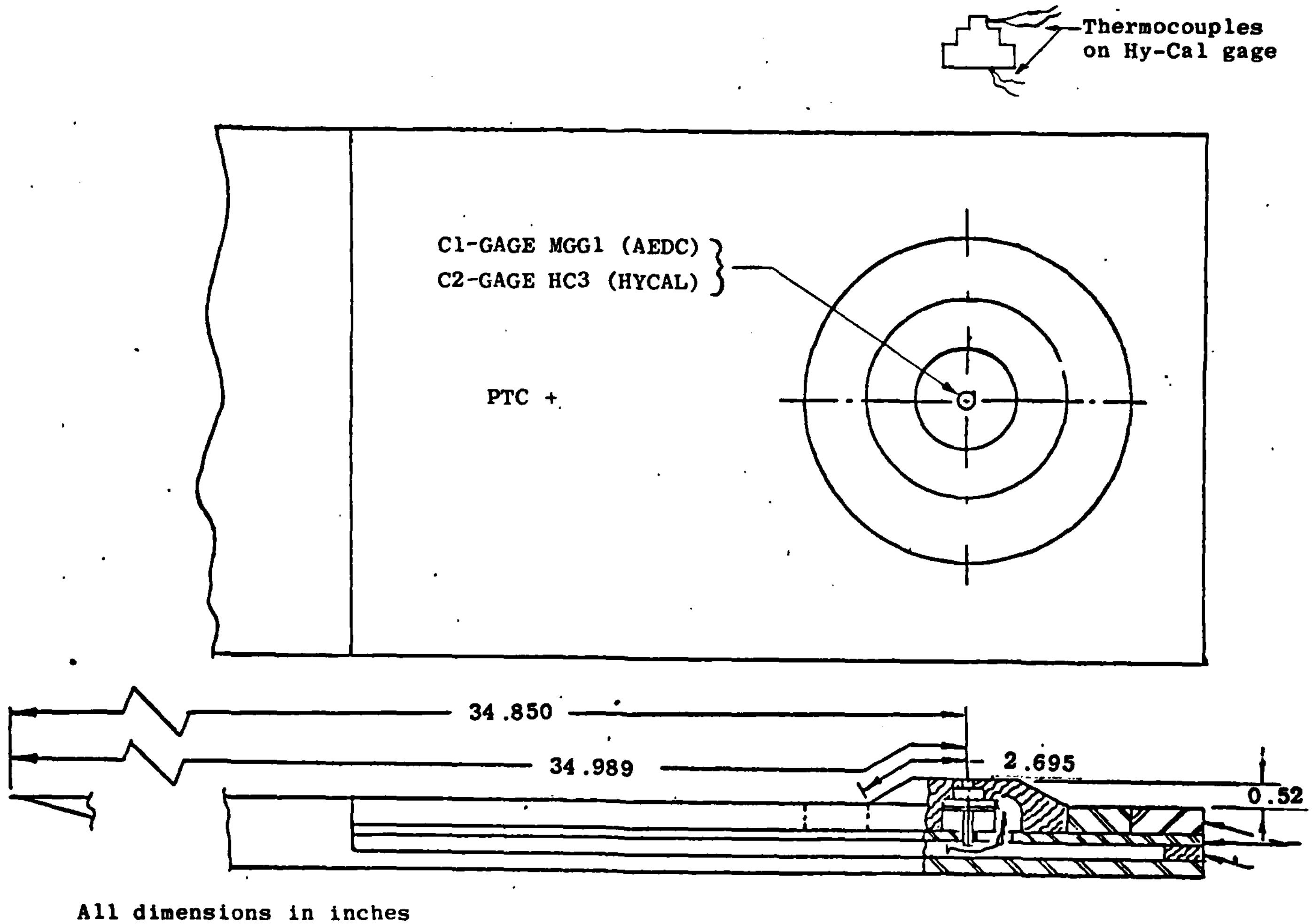


a. *Type A - Calibration Plate*
Figure 5. Model Details



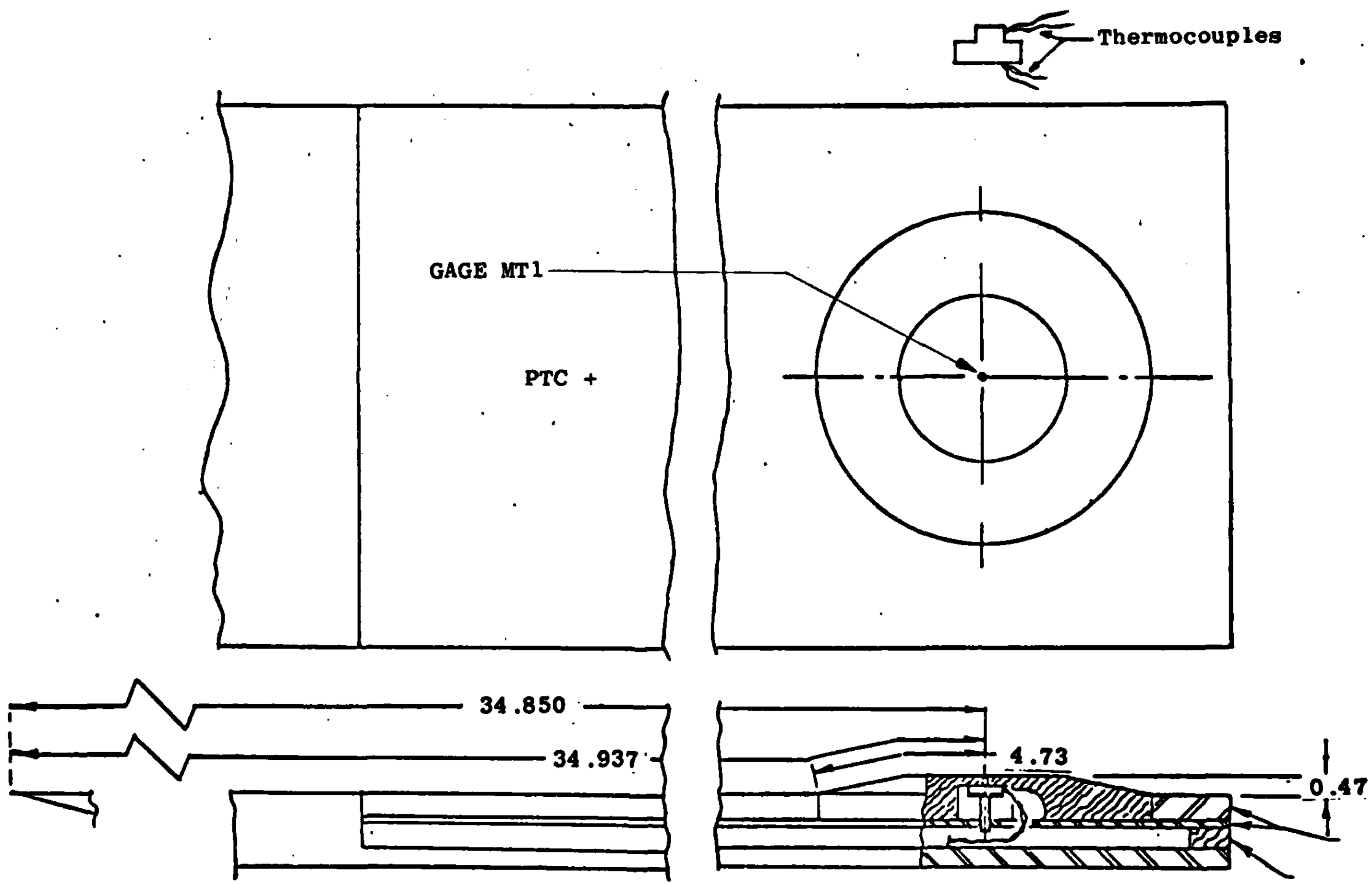
b. Models B1 and B2

Figure 5. Continued



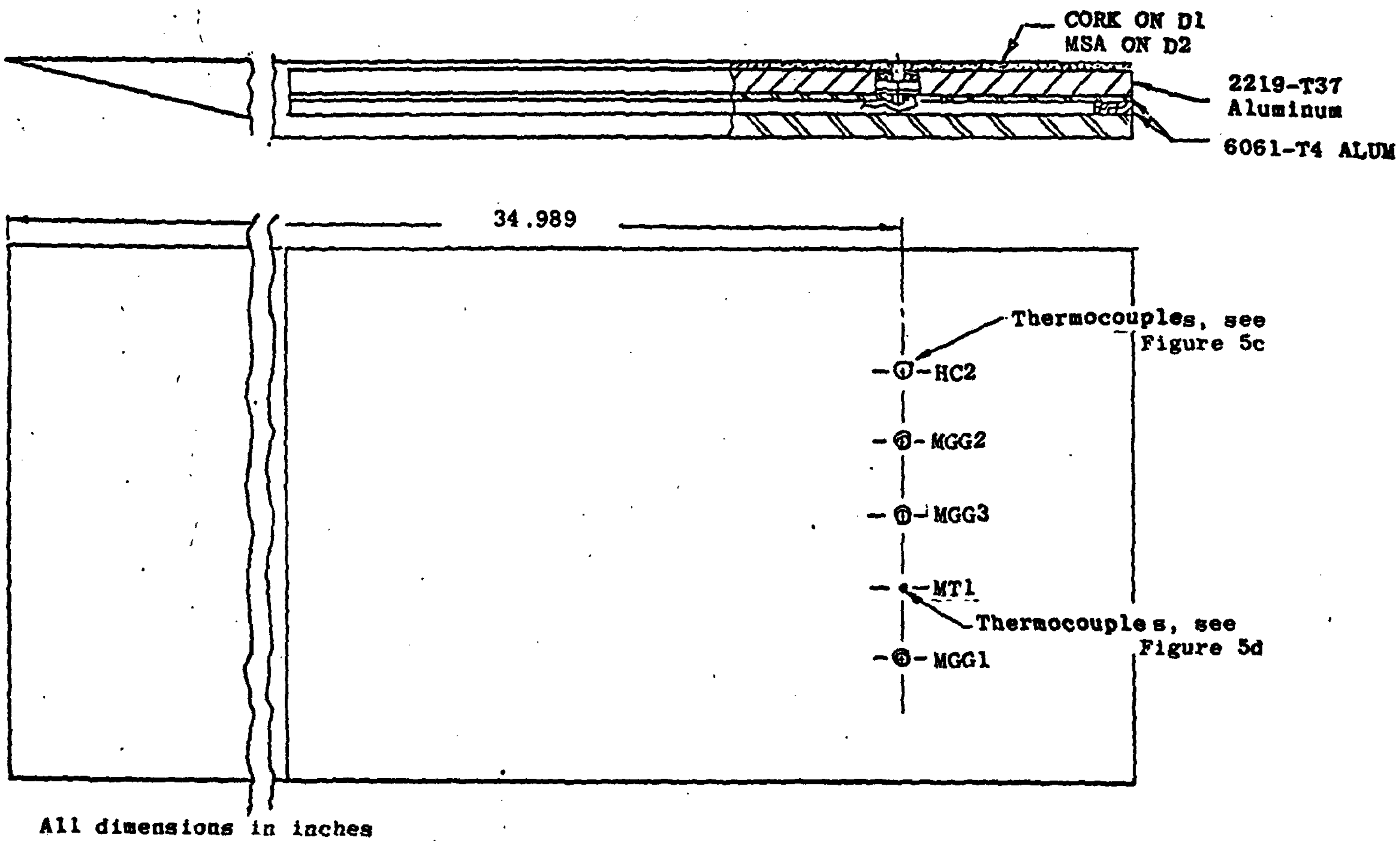
c. MODELS C1 and C2

Figure 5. Continued

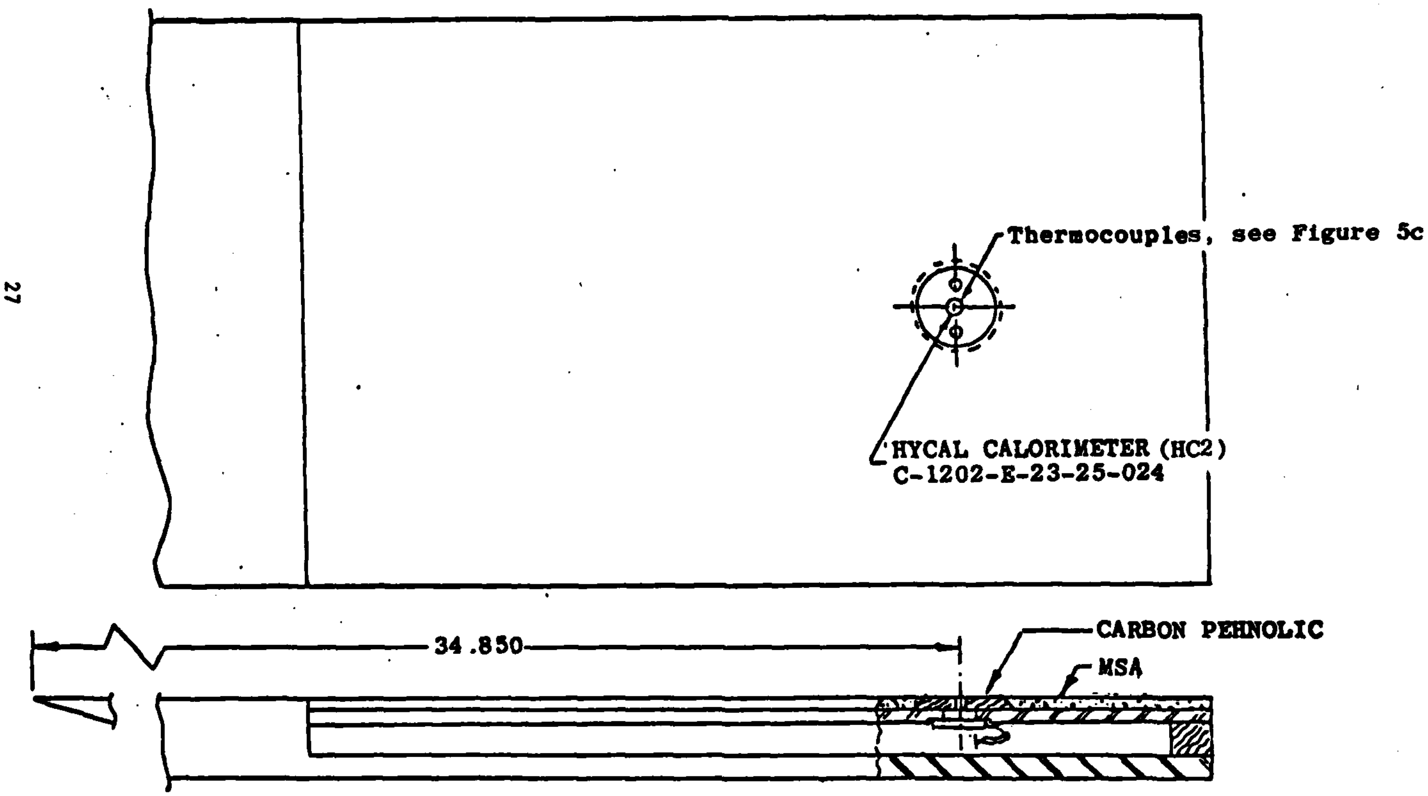


All dimensions in inches

d. MODEL C3
Figure 5. Continued

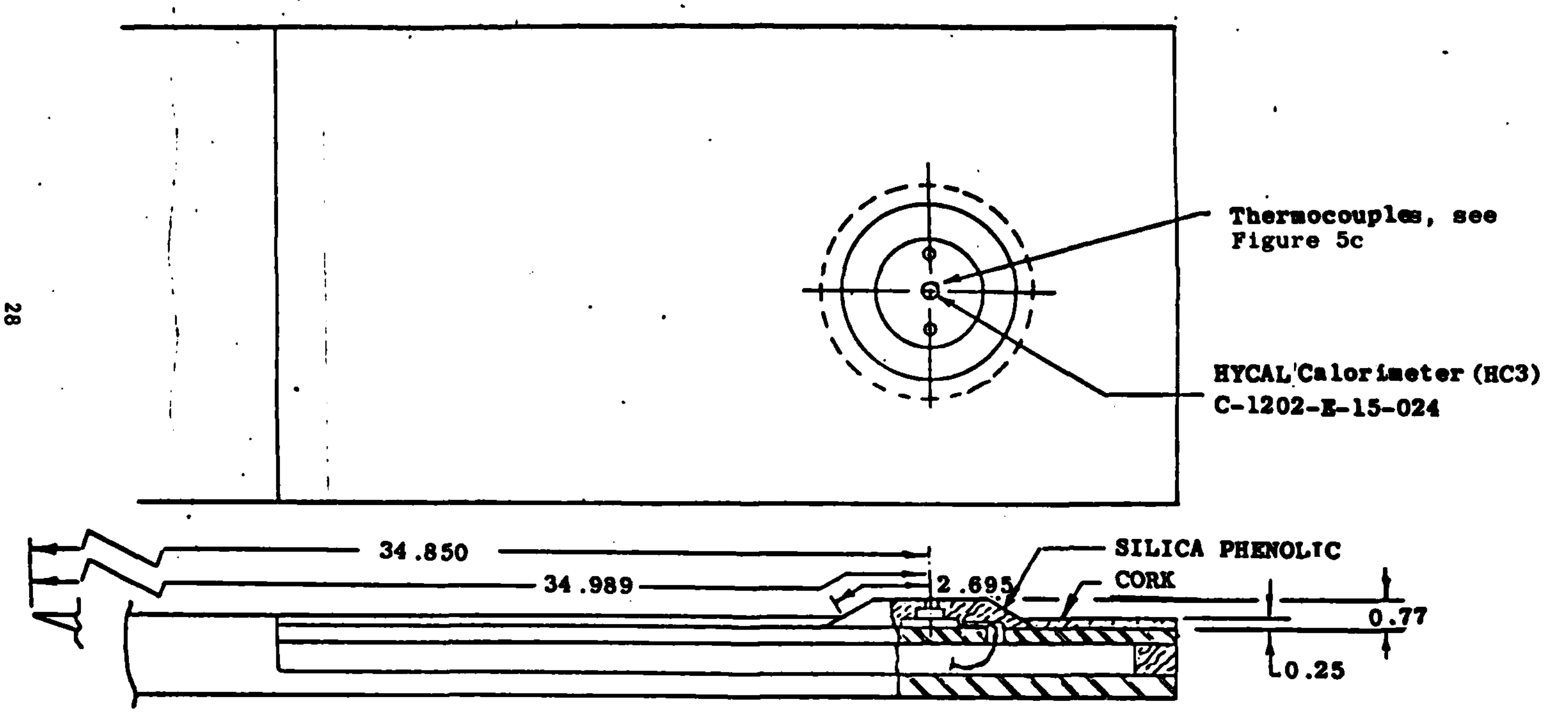


e. MODELS D1 and D2
Figure 5. Continued



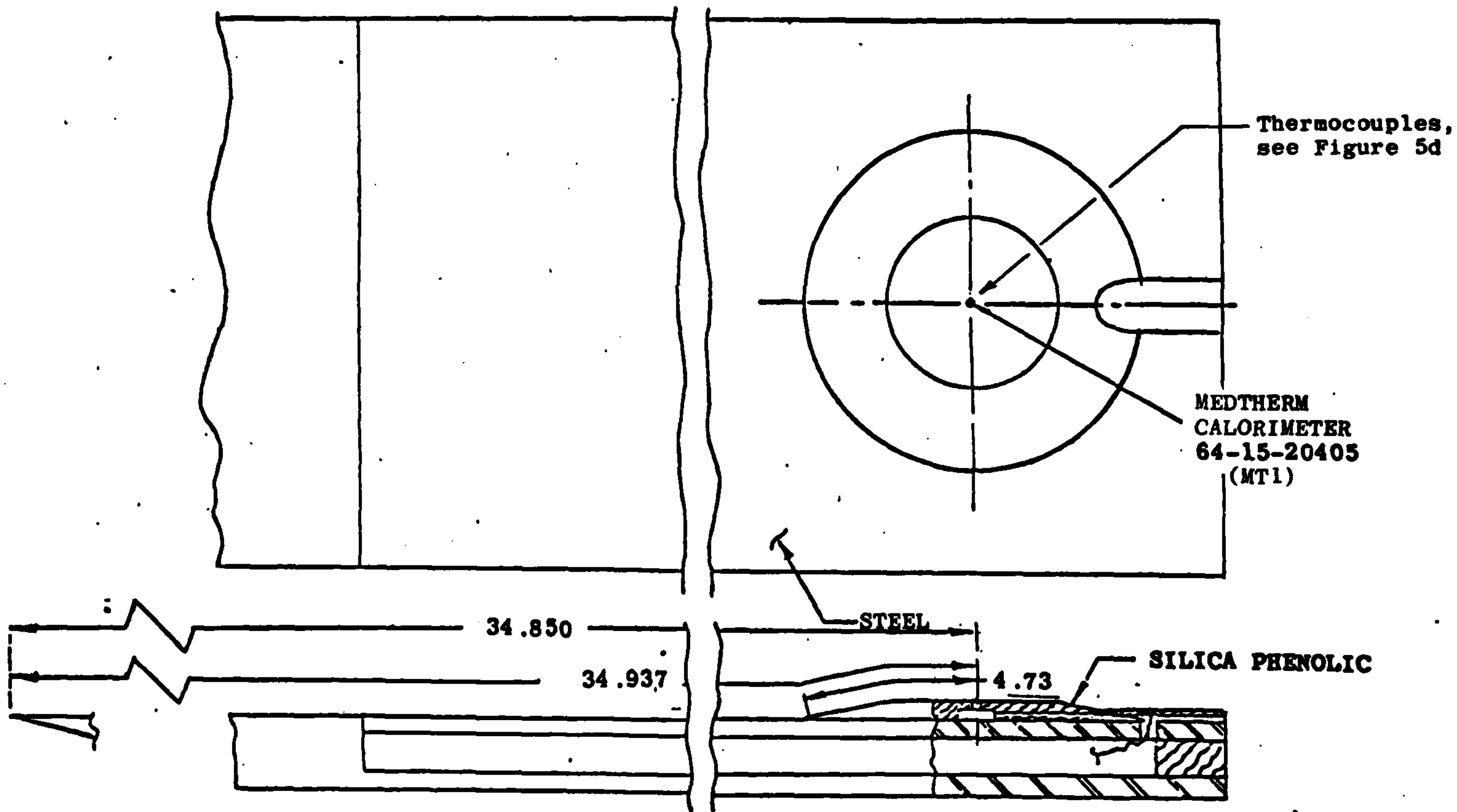
All dimensions in inches

f. MODEL E1 (Forward Skirt)
Figure 5. Continued



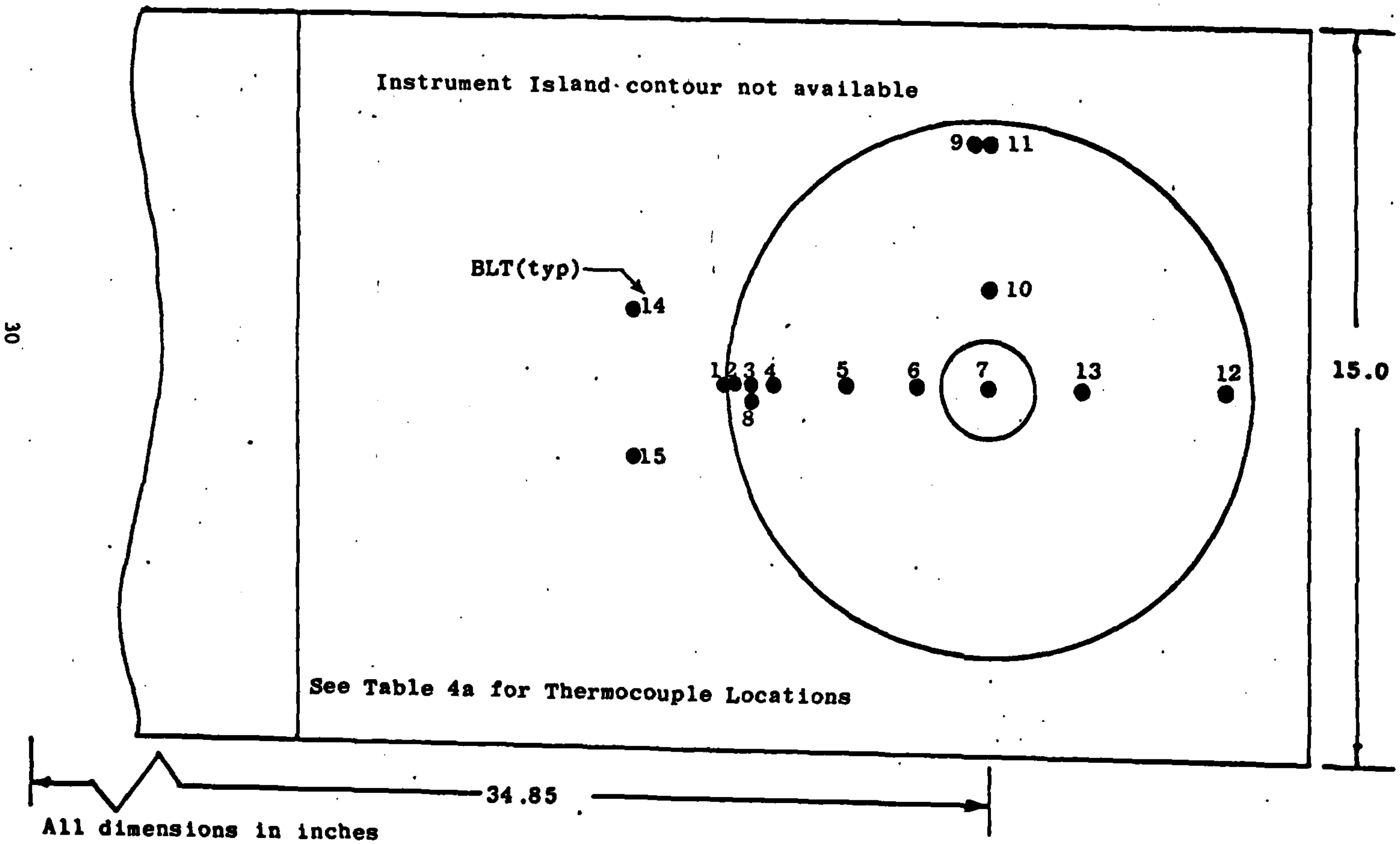
All dimensions in inches

g. MODEL E2 (Aft Skirt)
Figure 5. Continued

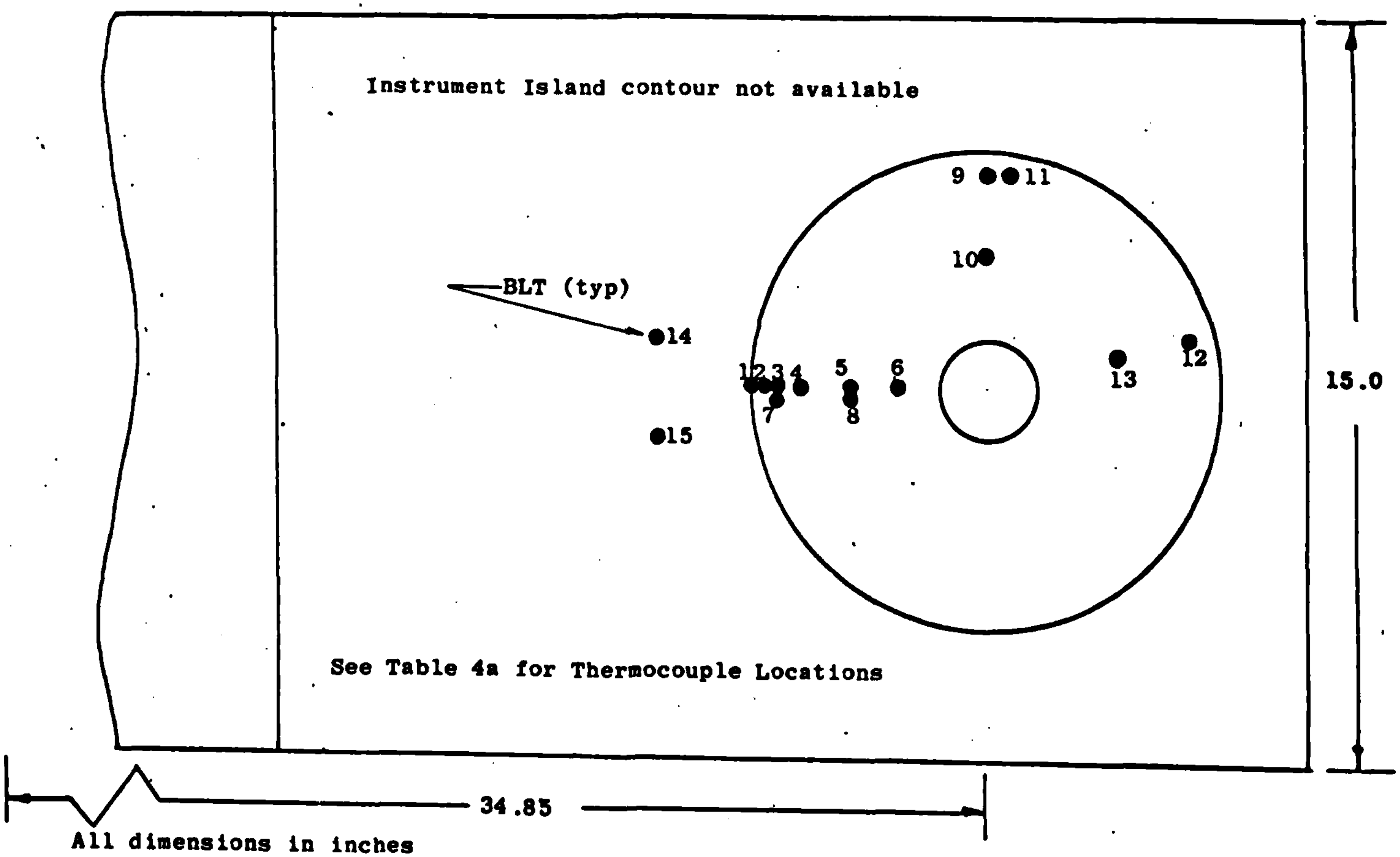


All dimensions in inches

h. MODEL E3 (SRM)
Figure 5. Continued

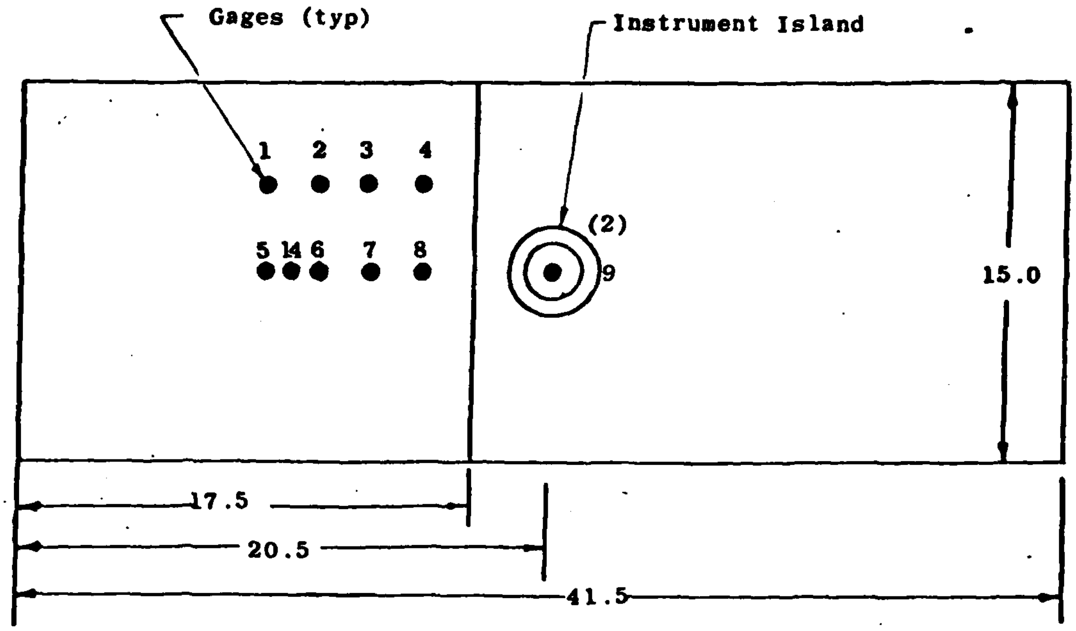


i. MODEL E4 WATER IMPACT FAIRING
Figure 5. Continued

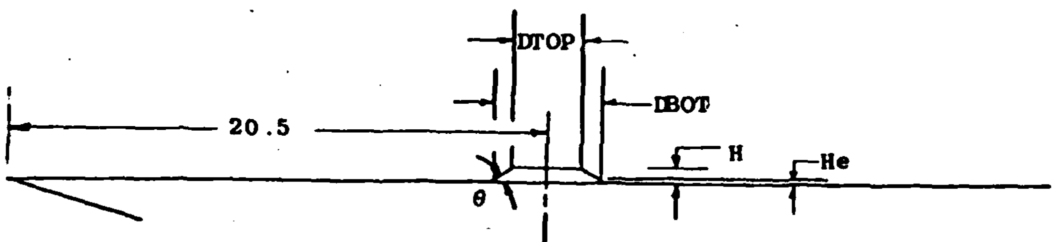


j. MODEL E5 ISLAND CALORIMETER FAIRING

Figure 5. Continued



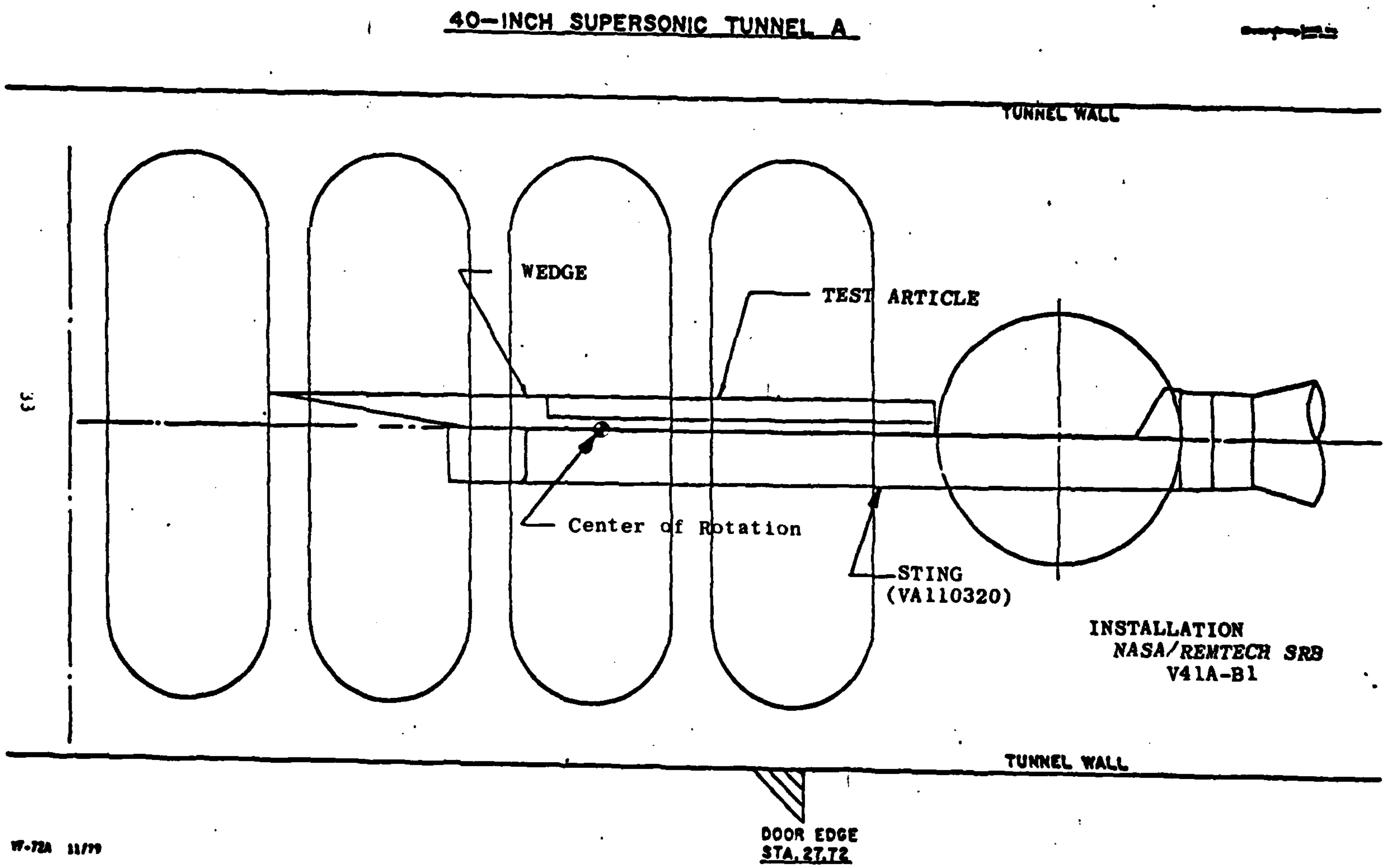
See Table 4b for Gardon Gage Locations and
Table 2a for Island Dimensions



(1) All dimensions in inches
(2) Models G and H only
(3) Only tested in Tunnel A

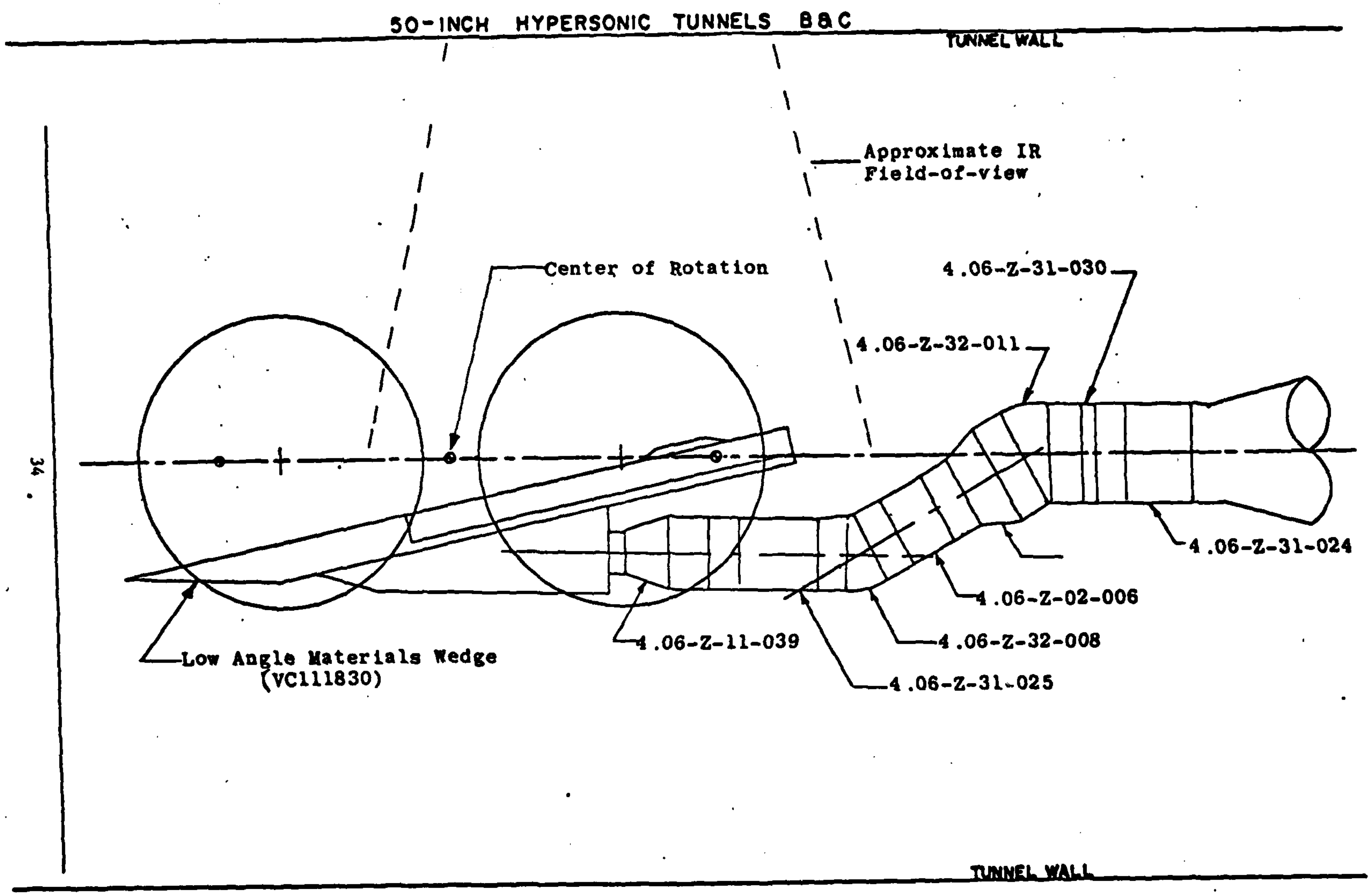
k. Models F, G, and H

Figure 5. Concluded



VF-72A 11/79

a. Tunnel A
Figure 6. Installation Sketches



b. Tunnel C
Figure 6. Concluded

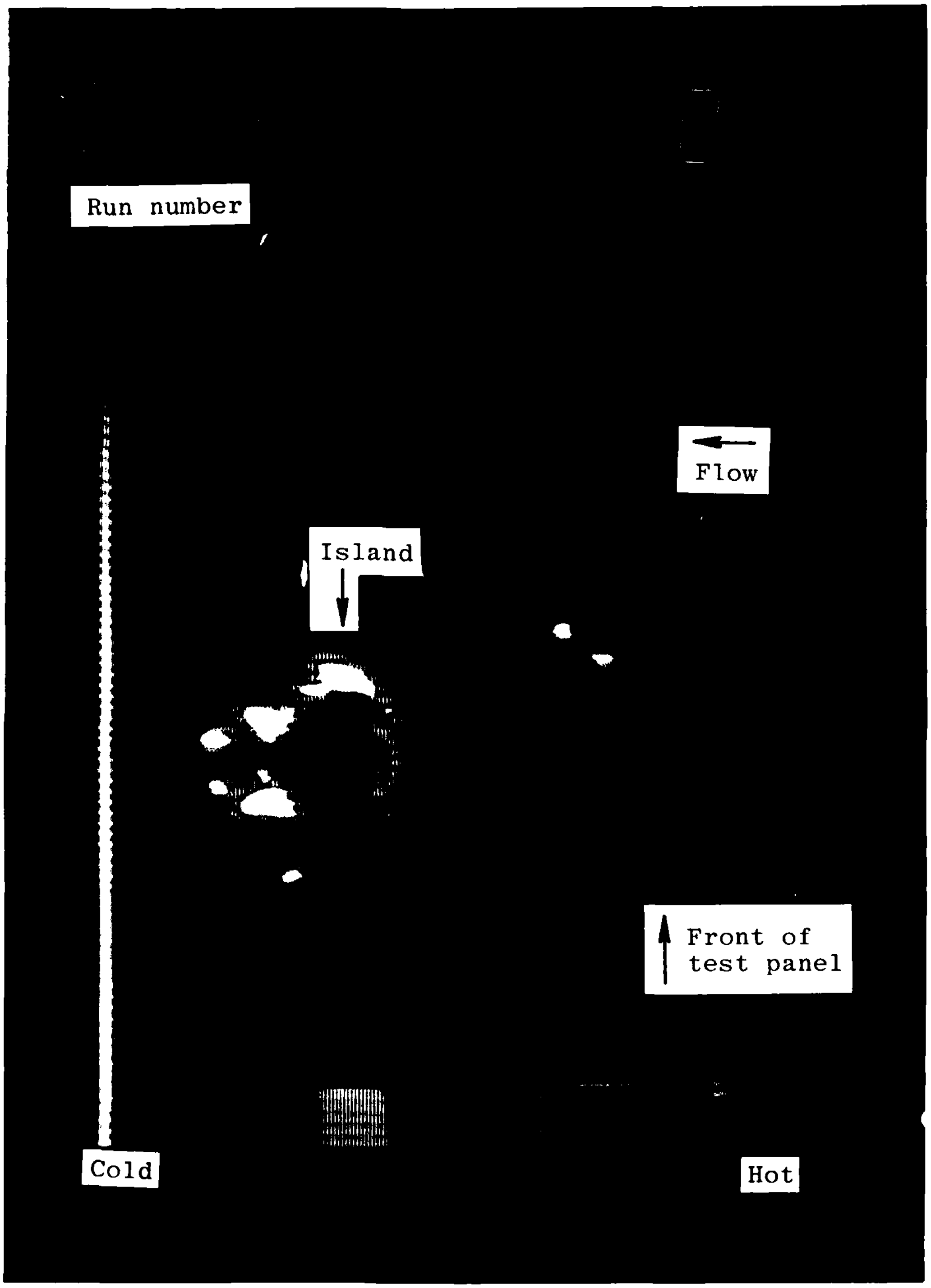


Figure 7. Sample Infrared Monitor Photograph

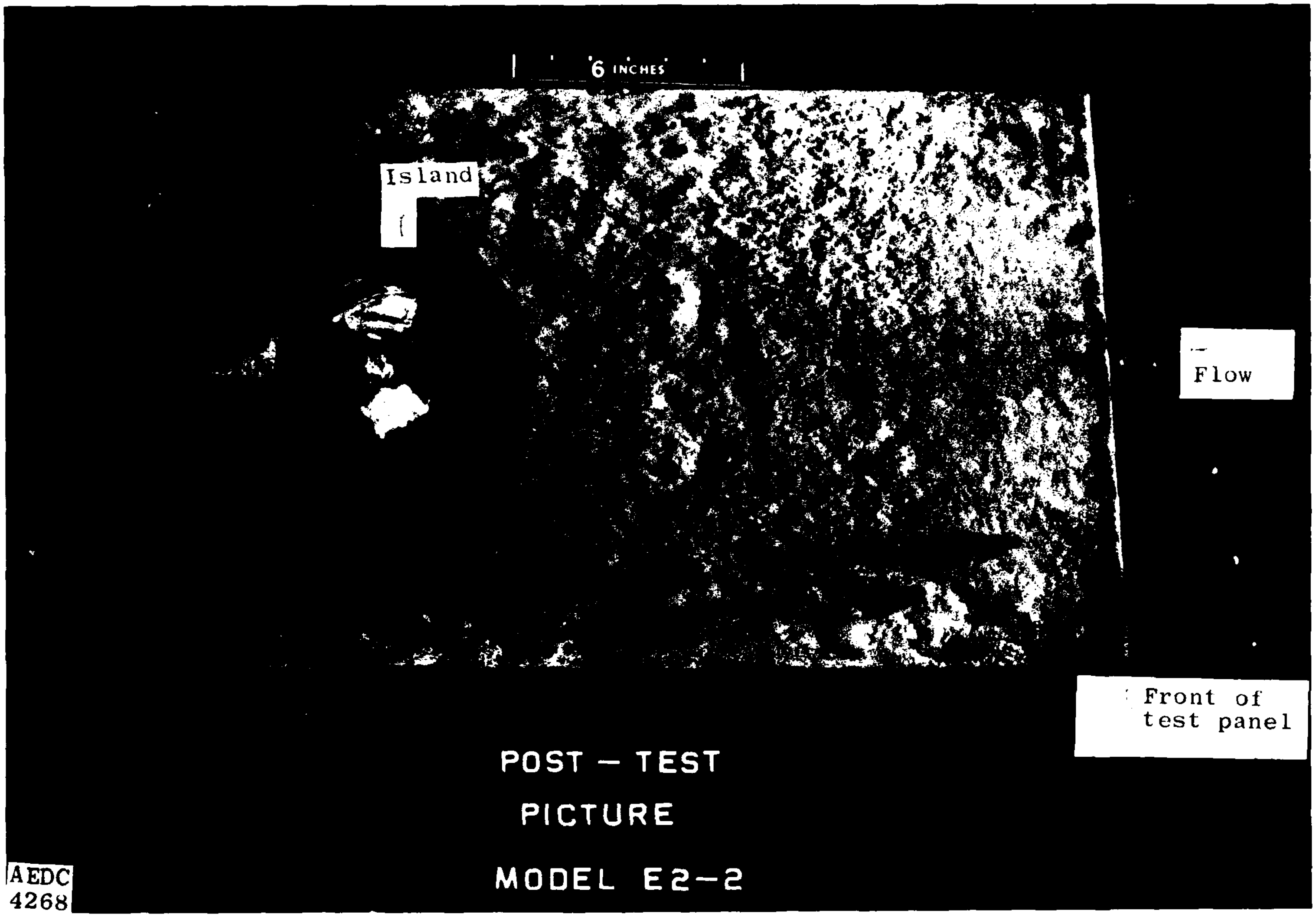


Figure 8. Typical Posttest Photograph

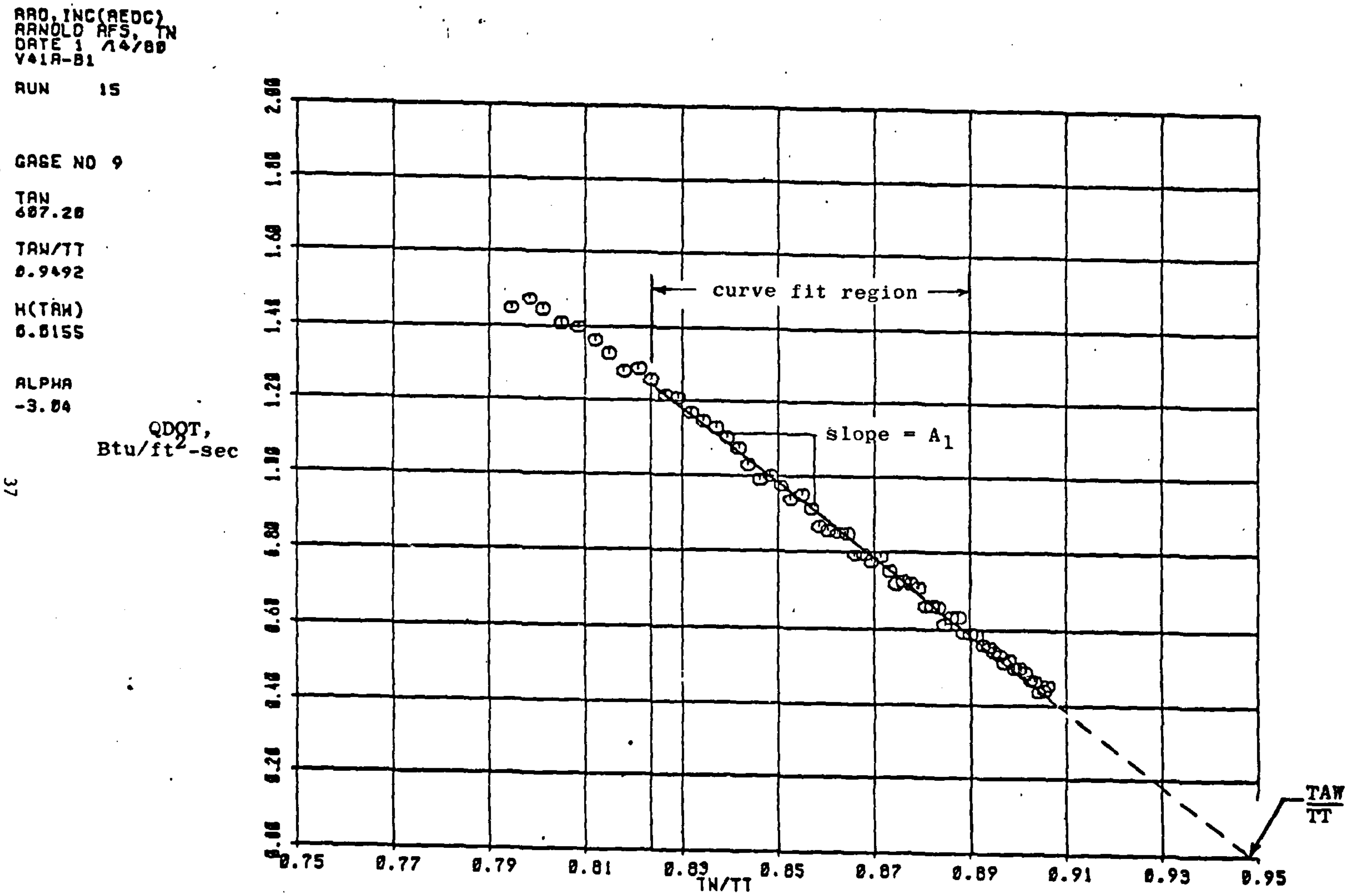
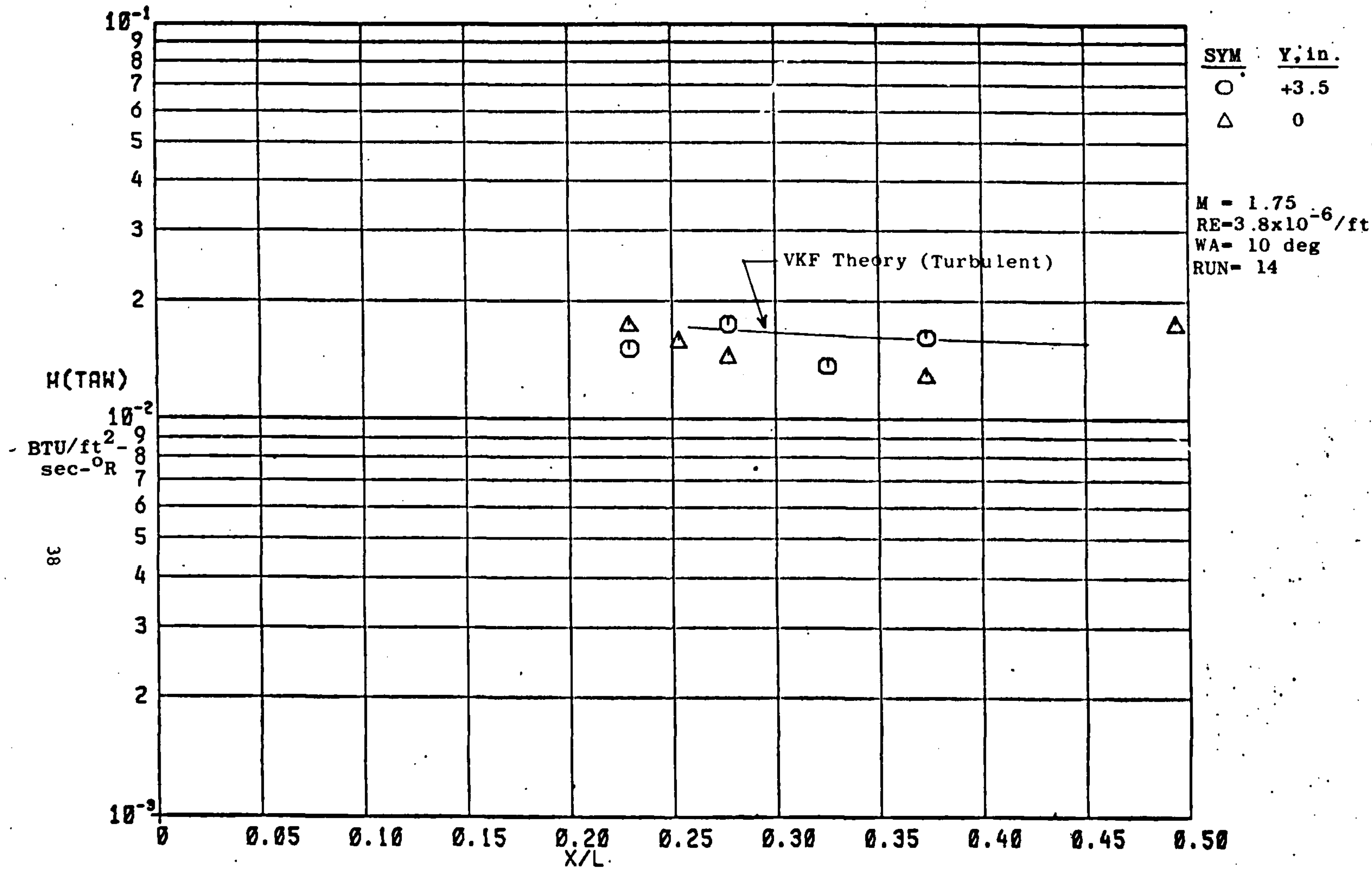
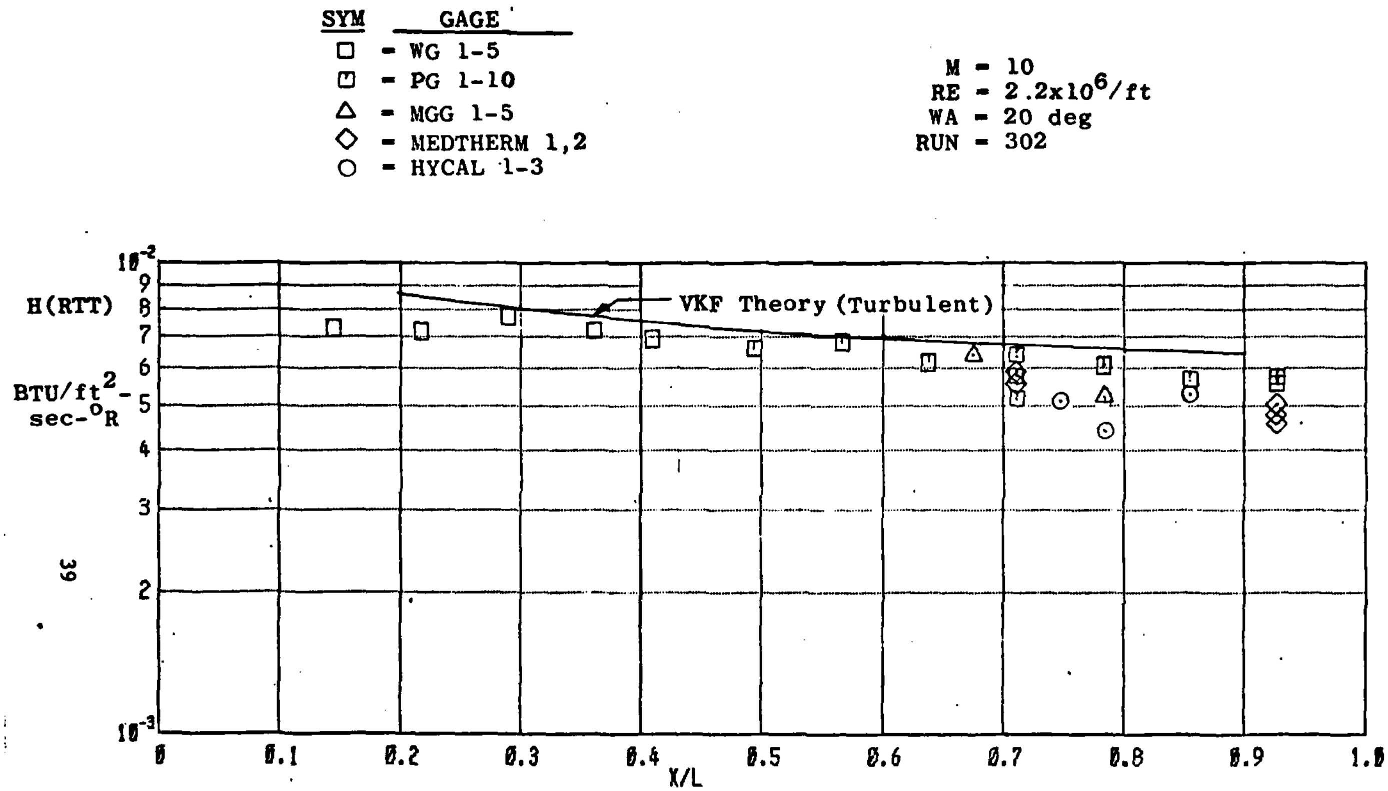


Figure 9. Typical QDOT vs. TW/TT Plot, Tunnel A



a. Tunnel A Entry

Figure 10. Typical Heat Transfer Data



Note: Not all gages are located on the model centerline (see Fig. 5a).

b. Tunnel C

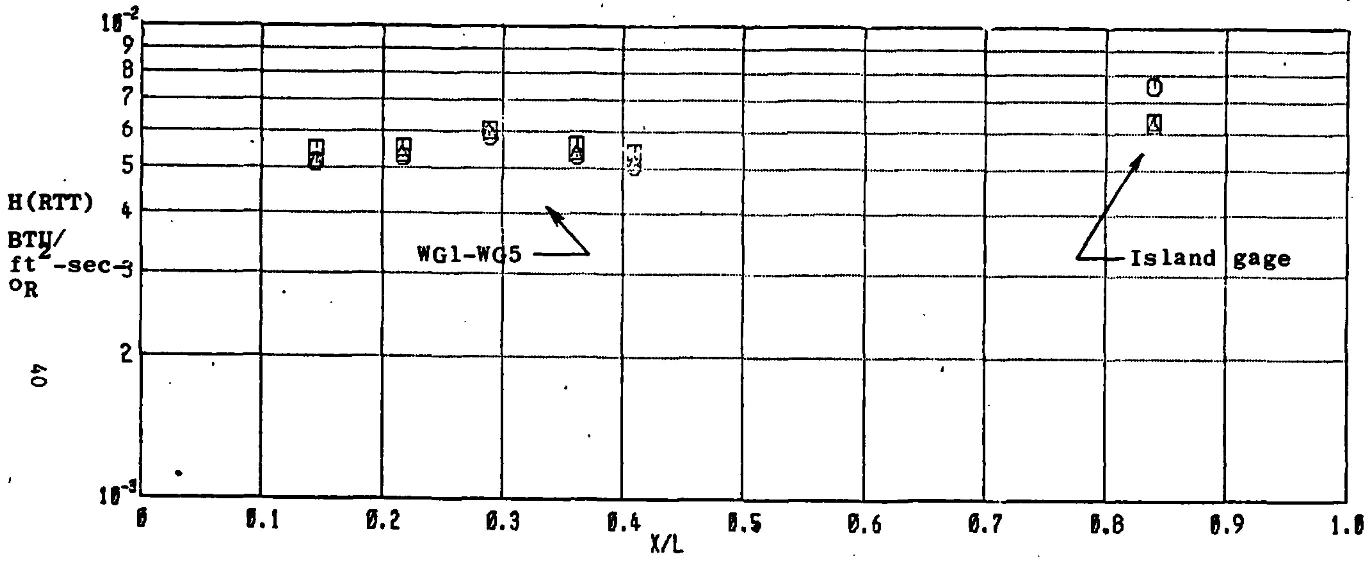
Figure 10. Continued

M = 10

WA = 15 deg

Sym	Run Number	Model	Island gage
□	9	C1	MGG1
○	12	C3	MT1
△	22	C2	HC3

Note: C3 Island geometry was different from C1 and C2



c. Gage Repeatability

Figure 10. Concluded

APPENDIX II

TABLES

TABLE 1

Model Categories

Category	Tunnel C	Tunnel A
Calorimeter Calibration Plate	Type A	Type F
Non-Isothermal Wall Plate	Type B	
Non-Isothermal Wall Plus Island	Type C	
Isothermal Wall Plus Island		Type G & H
Ablation Materials Plate	Type D	
Flight Duplication	Type E	

TABLE 2. Instrument Island Geometry

a. Tunnel A Models

CONFIG	θ,deg	H,in.	HE,in.	DTOP,in.	DBOT,in.
F	0	0	0	-	-
G1	30	0.056		0.356	0.550
G2		0.088		0.560	0.865
G3		0.115		0.732	1.130
G4		0.147		0.936	1.445
G5		0.175		1.114	1.720
G6		0.234		1.490	2.301
G7	↓	0.285	↓	1.814	2.801
H3	10	0.118	0.016	1.091	2.273
H5	10	0.175	0.022	1.684	3.457

b. Tunnel C Models

CONFIG	θ,deg	H,in.	HE,in.	DTOP,in.	DBOT,in.
A	0	0	0	-	-
B1	0	0	0	-	-
B2	0	0	0	-	-
C1	30	0.520	0	3.313	5.111
C2	30	0.520	0	3.313	5.111
C3	10	0.420	0	4.500	9.300
D1	0	0	0	-	-
D2	0	0	0	-	-
E1	0	0	0	-	-
E2	30	0.770	0	3.313	5.977
E3	10	0.420	0	4.500	9.300
E4	$\approx$ 10	-	0	-	11.000
E5	$\approx$ 10	-	0	-	9.600

TABLE 3. ESTIMATED UNCERTAINTIES

a. Basic Measurements
Tunnel C

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT*							Range	Type of Measuring Device	Type of Recording Device	Method of System Calibration
	Precision Index ± (S)			Bias ± (B)		Uncertainty ±(B + t_{95}S)					
	Percent of Reading	Unit of Measurement	Degree of Freedom	Percent of Reading	Unit of Measurement	Percent of Reading	Unit of Measurement				
ALPHI,deg		0.025	>30		0⁺		0.05	±15	Potentiometer	Digital data acquisition system analog-to-digital converter	Heidenhain rotary encoder ROD700 Resolution: 0.0006° Overall accuracy: 0.001°
E,mv	0.1		>30	0.01		(0.2% + 0.01)			DEC-10/Multiverter Preston amplifier		Millivolt standard, referenced to lab standard
PT,psia		0.62	>30	0.16		(0.16% + 1.24)		>500<2500	Wiancko variable reluctance pressure transducer	Digital data acquisition system analog-to-digital converter	In-place application of multiple pressure levels measured with a pressure measuring device calibrated in the standards laboratory
QDOT,BTU/ft^2-sec	1.5	0.015	>30 >30	2 2		(0.03 + 2%) 5		<1 1 to 10	Gardon gage	Digital data acquisition system analog-to-digital converter	Radiant heat source and secondary standard
TGE,°F		1 1 1 1	>30 >30 >30 >30	0.375	0.75 2 2		2.75 (2+0.375%) 4 4	-75 to 200 200 to 700 32 to 530 32 to 530	Thermocouple CuCn Thermocouple CrAl Thermocouple IC	Thermoplexer/Multiverter/RADS/ DEC-10 System	Voltage substitution calibration, secondary standard
TIME,sec		5x10^{-4}	>30	Runtime(sec)x5x10^{-6} ± [Runtime(sec)x 5x10^{-6} +10^{-3}]				ms to 365 days	Systron Donner time code generator	Digital data acquisition system	Instrument lab calibration against Bureau of Standards
TT,°F		1 1	>30 >30	0.375	2	(2 + 0.375%)	4	32 to 530 530 to 2300	Chromel[R]-Alumel[R] thermocouple	Doric temperature instrument digital multiplexer	Thermocouple verification of NBS conformity/voltage substitution calibration

*Thompson, J. W. and Abernethy, R. B. et al. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.
⁺Assumed to be zero

TABLE 3. Continued

a. Concluded
Tunnel A

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT*							Range	Type of Measuring Device	Type of Recording Device	Method of System Calibration
	Precision Index ±(S)			Bias ±(B)		Uncertainty ±(B + t_{95}S)					
	Percent of Reading	Unit of Measurement	Degree of Freedom	Percent of Reading	Unit of Measurement	Percent of Reading	Unit of Measurement				
ALPHI,deg		0.025	>30		0+		0.05	±15	Potentiometer	Digital data acquisition system analog-to-digital converter	Heidenhain rotary encoder ROD700 Resolution: 0.0006° Overall accuracy: 0.001°
E,mv	0.1		>30		0.01	(0.2% + 0.01)			DEC-10/Multiverter Preston Amplifier	Digital data system	Millivolt standard, referenced to lab standard
PT,psia		0.002 0.002 0.007	>30 >30 >30	 0.2 0.2	0.011	 (0.2% + 0.004) (0.2% + 0.014)	0.015	5.5 psi 15 60	Bell & Howell force balance pressure transducer	Digital data acquisition system analog-to-digital converter	In-place application of multiple pressure levels measured with a pressure measuring device calibrated in the standards laboratory
QDOT,BTU/ft^2-sec	 1.5	0.015	>30 >30	2 2		(0.03 + 2%) 5		<1 1 to 10	Gardon gage	Digital data acquisition system analog-to-digital converter	Radiant heat source and secondary standard
TGE,°F		1 1 1 1	>30 >30 >30 >30	 3/8	0.75 2 2	 (3/8% + 2)	2.75 4 4	-75 to 200 200 to 700 32 to 530 32 to 530	Thermocouple CuCn Thermocouple CrAl Thermocouple IC	Thermoplexer/Multiverter/RADS DEC-10 System	Voltage substitution calibration, secondary standard
TIME,sec		5x10^{-4}	>30	[Runtime(sec)x5x10^{-6}] ± [Runtime(sec) x5x10^{-6} +10^{-3}]				ms to 365 days	Systron Donner time code generator	Digital data acquisition system	Instrument lab calibration against Bureau of Standards
TT,°F		1	>30		2		4	0 to 300	Chromel®-Alumel® thermocouple	Doric temperature instrument digital multiplexer	Thermocouple verification of NBS conformity/voltage substitution calibration

*Thompson, J. W. and Abernethy, R. B. et al. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.
+Assumed to be zero

TABLE 3. Concluded
b. Calculated Parameters
Heat Transfer

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT[a]							Range
	Precision Index $\pm(S)$			Bias $\pm(B)$		Uncertainty $\pm(B + t_{95}S)$		
	Percent of Reading	Unit of Measurement	Degree of Freedom	Percent of Reading	Unit of Measurement	Percent of Reading	Unit of Measurement	
H(TAW),BTU/ft^2-sec-^oR, Tunnel A	7.0			0^+		14.0		All
H(TT),BTU/ft^2-sec-^oR, Tunnel C	2.0			2.0		6.0		All
M		0.08 0.04			0^+ 0^+		0.16 0.08	1.76,2.25,3.01 10
RE,ft^{-1}	0.36 0.46 0.49 1.11			0.46 0.48 0.47 0.45		1.18 1.40 1.45 2.67		3.8×10^6, M=1.76 4.7×10^6, M=2.26 4.1×10^6, M=3.01 2.2×10^6, M=10
TAW,^oR (for Tunnel A)	0.9			0.2		2.0		RE > 1.5×10^6
TW,^oR	0.2			0.4		0.8		All
WA,deg		0.05			0^+		0.10	All

[a]Abernethy, R. B. et al. and Thompson, J. W. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.
+Assumed to be zero

TABLE 4. Instrumentation Location

a. Tunnel C Models

Configuration	Gage Number	X/L	Y/B
All (1)	WG 1	0.145	0.000
	WG 2	0.217	
	WG 3	0.289	
	WG 4	0.361	
	WG 5	0.410	
A	PG 1	0.494	0.000
	PG 2	0.566	
	PG 3	0.639	
	PG 4	0.711	0.167
	PG 5		0.000
	PG 6		-0.167
	PG 7	0.783	0.000
	PG 8	0.855	
	PG 9	0.928	0.167
	PG 10	0.928	-0.167
	MGG 1	0.711	0.333
	MGG 2	0.711	-0.333
	MGG 3	0.928	0.333
	MGG 4		0.000
	MGG 5		-0.333
	MT 1	0.675	0.000
	MT 2	0.783	.167
	HC 1	0.747	0.000
	HC 2	0.783	-0.167
	HC 3	0.855	0.167
B1,B2	MGG 1	0.843	0.233
	MGG 2		0.633
	MGG 5		0.133
	MT 1		-0.133
	HC 2		0.267
	PTC (2)	0.536	0.042
C1,C2,C3	MGG 1 (3)	0.840	0.000
	HC 3 (4)		
	MT 1 (5)		
	PTC	0.547	
D1,D2	MGG 1	0.843	-0.267
	MGG 2		0.133
	MGG 3		0.000
	MT 1		-0.133
	HC 2		0.267

Configuration	Gage Number	X/L	Y/B
E1,E2	HC 2 (6)	0.840	0.000*
	HC 3 (7)	0.840	0.000
E3	MT 1	0.840	0.000
	BLT 1	0.724	
	2	0.730	
	3	0.736	
	4	0.748	
	5	0.772	
	6	0.796	
	7	0.736	0.017
	8	0.772	-0.017
	9	0.840	0.287
	10	0.834	0.287
	11	0.947	0.077
	12	0.676	0.067
	13	0.676	-0.067
E4	BLT 1	0.707	0.000
	2	0.713	
	3	0.719	
	4	0.731	
	5	0.767	
	6	0.804	
	7	0.840	
	8	0.719	-0.017
	9	0.840	0.333
	10	0.840	0.133
	11	0.834	0.333
	12	0.960	0.000
	13	0.888	0.000
	14	0.659	0.100
	15	0.659	-0.100
E5	BLT 1	0.724	0.000
	2	0.730	
	3	0.736	
	4	0.748	
	5	0.772	
	6	0.796	
	7	0.736	0.017
	8	0.772	0.017
	9	0.840	0.287
	10	0.840	0.187
	11	0.834	0.287
	12	0.947	0.074
	13	0.907	0.048
	14	0.676	0.067
	15	0.676	-0.067

b. Tunnel A Models

Configuration	Gage Number	X/L	Y/B
F,G,H	1	0.228	0.233
	2	0.277	
	3	0.325	
	4	0.373	
	5	0.228	0.000
	6	0.277	
	7	0.325	
	8	0.373	
	9	0.494	
	14	0.253	

NOTES:

(1) WG1-WG5 installed in all Tunnel C Models

(2) Configuration B1 only

(3) Configuration C1 only

(4) Configuration C2 only

(5) Configuration C3 only

(6) Configuration E1 only

(7) Configuration E2 only

TABLE 5. TEST SUMMARY

a. Tunnel A

M	1.76				2.26	3.01
$RE \times 10^{-6}$	3.84		1.68	0.60	4.74	4.08
CONFIG \ WA, deg	3	10	10	10	4	9
F	12, 15	10, 16	25	28	30	7
G1						9
G2						8
G3	20	19			31,32	10
G4	18	17	26			
G6	23	24		29		
H3		13				11
H5	22	21	27			

RUN NUMBER (TYP)

TABLE 5. Concluded

b. Tunnel C

WA, deg / CONFIG	10	12	15	17.5	20	25
A	1		2		3,5	4
B1					25	26
B2					27	28
C1			9		10	11
C2			15,22		16,23	17,24
C3			12		13	14
D1					31,34	30
D2						32,33
E1	19,20		18			
E2						29
E3	21	8				
E4				7		
E5				6		

Run number (typ)

Nominal Tunnel Parameters: MACH = 10.10
PT = 1760 psia
TT = 1900°R

TABLE 6. Color Interface Temperatures

Color Interface	F-STOP = 1.8			F-STOP = 3.6			F-STOP = 10		
	SENS=100			SENS = 1000			SENS = 1000		
	ϵ= .67	ϵ= .89	ϵ= .92	ϵ= .67	ϵ= .89	ϵ= .92	ϵ= .67	ϵ= .89	ϵ= .92
Black/Lt.Blue	557	542	540	557	542	540	55	541	540
Lt.Blue/Dk.Blue	584	567	566	811	780	777	1136	1080	1074
Dk.Blue/Green	599	581	579	872	836	832	1252	1185	1178
Green/Yellow	617	598	596	936	895	891	1380	1299	1290
Yellow/Red	627	608	606	977	933	928	1466	1375	1365
Red/Magenta	637	617	615	1009	962	957	1533	1434	1424
Magenta/Violet	646	625	623	1036	986	981	1591	1485	1474
Violet/Orange	653	632	630	1061	1009	1003	1647	1534	1522
Orange/Lt.Green	664	642	640	1096	1041	1035	1725	1602	1589
Lt.Green/White	670	648	646	1119	1061	1055	1778	1648	1634

Interface Temperature, °R (typ)

ϵ_{ref} = 1.00
T_{ref} = 536°R
lens angle = 25°

APPENDIX III

HEAT FLUX GAGE CALIBRATION RESULTS

APPENDIX III

HEAT FLUX GAGE CALIBRATION RESULTS

A variety of heat flux gages was utilized with the NASA/Remtech SRB Instrument Island test in Tunnel C. Twenty-five heat flux gages were initially installed in a large flat plate model in order to calibrate the tunnel flow at different angles of attack ranging from 10 to 25 degrees. A list of the gages is presented below:

1) Ten 10 mil, 1/4 in. diam. conventional, high temperature (1000°F) Gardon gages developed and fabricated by VKF;

2) Eight 10 mil, 1/4 in. diam. thermopile Gardon gages developed and fabricated by VKF;

3) Two 1/4 in. diam. Schmidt-Boelter gages developed and fabricated by VKF;

4) Three conventional Gardon type gages purchased by Remtech from Hy-Cal Engineering;

5) Two Schmidt-Boelter gages purchased by Remtech from Medtherm Corp.

Prior to the Tunnel C test, each of the gages listed above was calibrated in the VKF instrument lab using a six-element quartz tube lamp bank as the heat source. Although Remtech received calibration data with the purchase of the gages, it was deemed wise and consistent with good engineering practice to calibrate the commercial gages in the VKF facility. This decision was due in part to discrepancies in surface absorptivity detected on previous Hy-Cal and Medtherm gage calibrations when compared to VKF obtained values. In order to obtain consistent wind tunnel data, the VKF generated calibrations were used in heat-transfer data reduction.

The calibration procedures and calibration results are discussed below.

Calibration Procedure

The calibration procedure used for the commercial heat gages differed from that regularly used for VKF gage calibration. Ordinarily, transfer standard gages and test gages are irradiated simultaneously and the output signals from each are simultaneously measured (after allowing for stabilization) with an electronic sample-and-hold circuit. Because of the physical size and geometry of the holders containing the commercial gages, it was not possible to perform the calibration in the regular manner. The procedure used was to irradiate two transfer standard Gardon gages and simultaneously measure their output signals at a preset time. The incident heat flux level was determined by applying the proper calibration

factor to the output signals. Then, the commercial heat gage was physically positioned in the same relative location as the transfer standard Gardon gages. The commercial gage was then irradiated with the same heat flux level and its output was measured at the same relative time as the transfer standard gages. This procedure was repeated two or three times for each commercial gage at each heat flux level. Between runs the system was cooled so the initial temperature before each calibration was approximately 75°F. Taking the sensing surface absorptivity into account, the commercial gage scale factor was determined by dividing the calibration heat flux level by the gage output. This procedure was performed at two heat flux levels for each commercial gage.

Medtherm-Schmidt-Boelter Gages Results

Four different Medtherm Schmidt-Boelter gages were calibrated. Two were recently purchased by Remtech and two were purchased about one year ago. All four were of the same physical configuration which was a 0.170 in. diam. x 0.225 in. copper cylinder mounted on a copper heat sink plate from which the gage lead wires were taken. There were no internal thermocouples on any of the gages. Heat flux calibrations were performed on all four gages at calibration heat flux levels of approximately 2.0 and 3.0 BTU/ft^2-sec. Medtherm gage calibration results are shown in Table III-1.

The current VKF heat flux calibrations did not agree with the calibrations performed at Medtherm. In 1978, five VKF transfer standard Gardon gages were sent to Medtherm for calibration services. Those calibration results were very consistent, but disagreed with VKF calibrations by about 13.5% in the same direction as the calibration comparisons shown in Table III-1. In August 1979, VKF purchased three Schmidt-Boelter gages from Medtherm for tunnel evaluation purposes. The gages performed well in the wind tunnel measurement applications, but the calibrations differed from VKF calibrations by an average of 21%. This is about the same percentage difference noted in the comparison of the Medtherm gages recently purchased by Remtech with VKF calibrations (Table III-1).

Hy-Cal Gardon Gages Results

Four conventional (one differential thermocouple) Gardon gages were purchased by Remtech from Hy-Cal Engineering. The physical configuration of the Hy-Cal gages was a three-step copper circular cylinder. The first step was 0.375 in. diam. x 0.260 in., the second step was 0.875 in. diam. x 0.235 in., and the final step was 1.50 in. diam. x 0.250 in. A special heat sink calibration block was fabricated by the VKF to accommodate the Hy-Cal gages during calibration. Only three Hy-Cal gages were calibrated because one of the gages was damaged before delivery to VKF. These gages were fragile because of the very thin foil (0.0005 in.) required to achieve adequate sensitivity. The Hy-Cal gage calibrations were performed at one heat flux level, 3.0 BTU/ft^2-sec.

Because of discrepancies in sensing surface absorptivities detected in a previous calibration of Hy-Cal gages, these calibrations were performed in a manner designed to check the relative values of the sensing surface absorptivities used by Hy-Cal and VKF. Each Hy-Cal gage was irradiated two or three times with a known and constant incident heat flux level and the output signal was measured at a preset time point. This was done first with the Hy-Cal coating on the gage sensing surfaces. The Hy-Cal coating was then removed and the gage surfaces were coated with #1602 Krylon Ultra Flat Black spray enamel. Results of this experiment are shown in Columns #2 and #3 of Table III- 2. The ratios of the outputs with #1602 Krylon and the Hy-Cal coatings are shown in Column #4. These ratios should be 1.09 if the absorptivities are actually 0.97 and 0.89 as given. Actually all the ratios are less than 1.09. This could be caused by a relatively thick (0.0005 in.) surface coating applied on a very thin foil. However, the experimental results did show there was a significant and easily detectable difference in gage outputs with the different surface coatings.

The data shown in Table III-2 can also be used to make comparisons of Hy-Cal and VKF heat flux calibrations. Gage scale factors generated by the manufacturer (Hy-Cal) are given in Column #5. Scale factors obtained by experimental calibrations at VKF are shown in Columns #6 and #8 for different sensing surface absorptivities. The ratio of the VKF generated scale factors to the manufacturer's scale factors is shown in Columns #7 and #8. The agreement is within ±6% for Hy-Cal gages #73488 and #75644, but the agreement is about -20% for gage #73487. The low scale factor for gage #73487 indicates a higher gage output than shown by the manufacturer's calibration data. This could have been caused by the gage foil becoming separated from the heat sink. This speculation was somewhat substantiated by the fact that this gage failed during the course of the Tunnel C test. The comparison of Hy-Cal gage calibration data obtained by VKF and the manufacturer is not as good as desired, but no specific trend or bias is shown.

Post-Test Calibrations Results

After the completion of the Tunnel C tests, all gages were removed and calibrations were performed on all gages which were operational. The results of those calibrations are shown in Table III-3. No calibration data are shown for the high temperature Gardon gages (WG1-WG5) in the model wedge since they were not removed from the wedge. No calibration data are shown for Gardon gages PG3 and HC2 since these gages were damaged either during the course of the test or during removal from the test model. The post-test calibration data agree very well with pre-test calibrations, all being within ±3%.

Concluding Remarks

Experimental calibrations by the VKF of Medtherm and Hy-Cal heat flux gages, purchased by Remtech for the Tunnel C test, showed the same general trends as detected from the most recent VKF experience with heat flux gages and/or calibrations from the same companies. Agreement with the Medtherm calibrations was not good, a difference of 21 percent was observed. Agreement with Hy-Cal calibrations was good (±6 percent), although there was some discrepancy involving sensing surface absorptivity.

TABLE III-1

COMPARISON OF VKF AND MEDTHERM HEAT FLUX CALIBRATIONS

Medtherm Schmidt-Boelter Gage Serial Number	Gage Calibration Factor,(3) $\frac{BTU/Ft^2\text{-Sec.}}{mv}$	GAGE CALIBRATION FACTOR, $\frac{BTU/Ft^2\text{-Sec.}}{mv}$				$\left(\frac{\text{VKF Scale Factor}}{\text{Medtherm Scale Factor}}\right)$
		Pre-Test Calibration $\dot{q} \cong 2.0 \frac{BTU}{Ft^2\text{-Sec.}}$	Pre-Test Calibration $\dot{q} \cong 3.0 \frac{BTU}{Ft^2\text{-Sec.}}$	Average Pre-Test Calibration	Post-Test Calibration	
6191(1)	0.692	0.776	0.785	0.781	--	1.13
6192(1)	0.718	0.776	0.796	0.786	--	1.10
325801(2)	1.138	1.39	1.37	1.38	1.36	1.21
325805(2)	1.125	1.38	1.38	1.38	1.37	1.23

(1)These gages purchased by Remtech June 1979.

(2)These gages purchased by Remtech April 1980.

(3)This calibration performed at Medtherm.

TABLE III-2

COMPARISON OF VKF AND HY-CAL HEAT FLUX CALIBRATIONS

Hy-Cal Gardon Gage Serial Number	Incident Heat Flux Applied to Gage: $\dot{q}_o$ = 3.01 BTU/Ft²-Sec.		Output With Krylon Coating / Output With Hy-Cal Coating	Manufacturer's Scale Factor	VKF Generated Scale Factor	(VKF Generated Scale Factor) / (Manufacturer's Scale Factor)	VKF Generated Scale Factor	(VKF Generated Scale Factor) / (Manufacturer's Scale Factor)
	Average Gage Output (Hy-Cal Coating) (mv)	Average Gage Output (Krylon #1602 Coating) (mv)		$\left(\frac{BTU/Ft^2\text{-}Sec}{mv}\right)$ (3)	A = 0.89 $\left(\frac{BTU/Ft^2\text{-}Sec}{mv}\right)$		A = 0.97 $\left(\frac{BTU/Ft^2\text{-}Sec}{mv}\right)$	
Col 1	2	3	4	5	6	7	8	9
73487 (1)	3.38	3.51	1.038	1.007	0.792	0.786	0.832	0.826
73488 (1)	1.89	2.00	1.058	1.51	1.42	0.940	1.46	0.967
75644 (2)	1.27	1.33	1.047	2.08	2.11	1.014	2.19	1.052

(1) These gages purchased by Remtech May 1979.

(2) This gage purchased by Remtech November 1979.

(3) This calibration performed at Hy-Cal Engineering.

A = surface absorptivity ratio

TABLE III-3

Comparison of Pretest and Posttest Calibration Results

Heat Gage Serial Number	Model Location	Type Gage	Pre-Test Calibration Factor, (BTU/Ft²-Sec / mv)	Post-Test Calibration Factor, (BTU/Ft²-Sec / mv)	(Post-Test Cal. / Pre-Test Cal.)
	WG1 ↓ WG5	1/4 in. dia. high temperature Gardon gage			
10T293	PG1	1/4 in. dia. thermopile Gardon gage	0.582	0.582	1.00
10T298	PG2	1/4 in. dia. thermopile Gardon gage	0.588	0.580	0.986
10T299	PG3	1/4 in. dia. thermopile Gardon gage	0.785		
325801	MT1	Medtherm Schmidt-Boelter gage	1.38	1.36	0.986
10HT19	MGG1	1/4 in. dia. high temperature Gardon gage	7.53	7.34	0.975
SB80X2	P64	1/4 in. dia. VKF Schmidt-Boelter gage	0.320	0.317	0.991
10T347	PG5	1/4 in. dia. thermopile Gardon gage	0.688	0.691	1.004
10T14	PG6	1/4 in. dia. thermopile Gardon gage	0.660	0.660	1.00
10HT25	MGG2	1/4 in. dia. high temperature Gardon gage	9.24	9.23	0.999
73488	HC1	Hy-Cal Gardon gage	1.45	1.49	1.028
325805	MT2	Medtherm Schmidt-Boelter gage	1.38	1.37	0.993
20T323	PG7	1/4 in. dia. thermopile Gardon gage	1.29	1.25	0.969
73487	HC2	Hy-Cal Gardon gage	0.830		
75644	HC3	Hy-Cal Gardon gage	2.19	2.20	1.005
SB80X3	PG8	1/4 in. dia. VKF Schmidt-Boelter gage	1.23	1.27	1.033
10HT40	MGG3	1/4 in. dia. high temperature Gardon gage	7.43	7.35	0.989
10T387	PG9	1/4 in. dia. thermopile Gardon gage	0.689	0.688	0.999
10HT14	MGG4	1/4 in. dia. high temperature Gardon gage	8.81	8.79	0.998
10T384	PG10	1/4 in. dia. thermopile Gardon gage	0.645	0.633	0.981
10HT22	MGG5	1/4 in. dia. high temperature Gardon gage	7.60	7.60	1.00

APPENDIX IV

SAMPLE TABULATED DATA

ARO, INC. - AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
NASA REMTECH SRB INSTRUMENT ISLAND

DATE COMPUTED 15-FEB-80
TIME COMPUTED 07:54:08
DATE RECORDED 14-JAN-80
TIME RECORDED 13:59:51
PROJECT NUMBER V41A-01

RUN	ISLAND	M	WA DEG	RE FT-1	PT PSIA	TT DEGR
7	FO	3.01	9.08	4.095E+06	37.23	680.67

T DEGR	P PSIA	Q PSIA	V FT/SEC	RHO LBM/FT3	MU LB-SEC/FT2
242.06	1.00	6.332	2296.	1.113E-02	1.94E-07

GAGE	X/L	Y/R	TAW DEGR	TAW/TT	H(TAW) BTU/FT2-SEC-R	QCW BTU/FT2-SEC
1	0.229	0.233	656.2	0.964	1.067E-02	2.097E+00
2	0.277	0.233	662.0	0.973	1.121E-02	2.267E+00
3	0.325	0.233	653.9	0.961	8.771E-03	1.704E+00
4	0.373	0.233	662.8	0.974	9.814E-03	1.994E+00
5	0.229	0.000	659.0	0.968	1.128E-02	2.248E+00
6	0.277	0.000	651.0	0.956	1.056E-02	2.022E+00
7	0.325	0.000	654.0	0.961	9.894E-03	1.922E+00
8	0.373	0.000	663.1	0.974	8.944E-03	1.820E+00
9	0.494	0.000	624.6	0.918	1.321E-02	2.178E+00
10	DELETE					
11	DELETE					
12	DELETE					
13	DELETE					
14	0.253	0.000	655.2	0.963	1.069E-02	2.089E+00

TP = 576.13 DEG R

1. Heat Transfer Data, Tunnel A

ARO, I - AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
NASA/REMTECH SPB INST TSL

DATE COMPUTED 29-MAY-80
TIME COMPUTED 07:32:08
DATE RECORDED 3-MAY-80
TIME RECORDED 4: 1:15
PROJECT NUMBER V41C-B1

RUN	CONFIGURATION	M	WA DEG	RE FT-1	PT PSIA	TT DEG R	F-STOP
3	CAL PLATE	10.10	20.01	2.182E+06	1765.0	1897.7	1.8

T DEG R	P PSIA	Q PSIA	V FT/SEC	RHO LBM/FT3	MU LBF-SEC/FT2	TIME SEC	SENS
93.43	0.04	2.72	4784.9	1.103E-03	7.518E-08	4.92	100.

GAGE	X/L	Y/B	TGE DEG R	TW DEG R	QDOT BTU/FT2-SEC	H(TT) BTU/FT2-SEC-R	H(0.918*TT) BTU/FT2-SEC-R	QDOT-0 BTU/FT2-SEC
WG1	0.145	0.000	561.7	596.3	8.36	6.425E-03	7.297E-03	9.238E+00
WG2	0.217	0.000	557.0	593.9	8.25	6.327E-03	7.184E-03	9.098E+00
WG3	0.289	0.000	550.1	590.7	8.89	6.803E-03	7.722E-03	9.782E+00
WG4	0.361	0.000	545.9	571.3	8.46	6.378E-03	7.225E-03	9.171E+00
WG5	0.410	0.000	546.3	574.7	8.08	6.108E-03	6.922E-03	8.784E+00
PG1	0.494	0.000	537.4	576.8	7.69	5.825E-03	6.603E-03	8.377E+00
PG2	0.566	0.000	527.4	568.2	8.00	6.019E-03	6.817E-03	8.656E+00
PG3	0.639	0.000	519.6	556.7	7.31	5.449E-03	6.165E-03	7.836E+00
PG4	0.711	0.167	512.6	579.1	7.42	5.674E-03	6.377E-03	8.088E+00
PG5	0.711	0.000	501.4	533.8	6.23	4.571E-03	5.159E-03	6.573E+00
PG6	0.711	-0.167	512.8	548.4	6.92	5.128E-03	5.797E-03	7.374E+00
PG7	0.783	0.000	493.5	512.9	7.46	5.391E-03	6.073E-03	7.752E+00
PG8	0.855	0.000	489.7	506.9	6.91	4.968E-03	5.594E-03	7.144E+00
PG9	0.928	0.167	491.9	527.5	6.84	4.989E-03	5.628E-03	7.174E+00
PG10	0.928	-0.167	490.0	526.3	6.96	5.075E-03	5.724E-03	7.297E+00
MGG1	0.711	0.333	521.6	551.8	6.64	4.933E-03	5.578E-03	7.094E+00
MGG2	0.711	-0.333	519.5	545.6	7.06	5.222E-03	5.902E-03	7.510E+00
MGG3	0.928	0.333	501.2	527.0	5.55	4.048E-03	4.566E-03	5.820E+00
MGG4	0.928	0.000	487.9	511.4	5.92	4.274E-03	4.814E-03	6.146E+00
MGG5	0.928	-0.333	502.4	530.1	6.10	4.460E-03	5.033E-03	6.414E+00
MT11	0.675	0.000	519.6	519.6	7.90	5.733E-03	6.462E-03	8.244E+00
MT12	0.675	0.000	496.7					
MT21	0.783	0.167	495.9	495.9	6.53	4.658E-03	5.239E-03	6.698E+00
MT22	0.783	0.167	487.3					
HC11	0.747	0.000	502.1	502.1	6.38	4.574E-03	5.148E-03	6.578E+00
HC12*	0.747	0.000	497.7					
HC21	0.783	-0.167	497.7	497.7	5.47	3.904E-03	4.392E-03	5.614E+00
HC22	0.783	-0.167	489.7					
HC31	0.855	0.167	499.0	499.0	6.61	4.724E-03	5.315E-03	6.792E+00
HC32	0.855	0.167	482.0					

2. Heat Transfer Data, Tunnel C

DATE
ILMED
- 8